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# Microgravity Combustion Science: Progress, Plans, and Opportunities

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# CONTENTS

# INTRODUCTION

The study of fundamental combustion processes in a microgravity environment is a relatively new scientific endeavor. A few simple, precursor experiments were conducted in the early 1970's. Today, the advent of the U.S. Space Shuttle and the anticipation of Space Station *Freedom* provide for scientists and engineers a special opportunity—in the form of long-duration microgravity laboratories—and need—in the form of spacecraft fire safety—to pursue fresh insight into the basic physics of combustion.

In a recent independent assessment, Professor G. Faeth noted that the influence of gravity "is so ubiquitous that we tend not to recognize the enormous negative impact that it has had on the rational development of combustion science." Through microgravity, a new range of experiments can be performed since

(1) *Buoyancy-induced flows are nearly eliminated.* Because of the hot, less dense reaction products of combustion, buoyancy-induced flows tend to develop in normal-gravity experiments, promoting self-turbulization and instabilities. Microgravity reduces these flows and their attendant complications, thus, furthering understanding not only of reduced-gravity behavior but also, by direct comparison, related normal-gravity combustion processes.

(2) *Normally obscured forces and flows may be isolated.* Buoyancy frequently obscures weaker forces, such as electrostatic, thermocapillary, and diffusional forces, which may be important near flammability limits. Further, the effect of low-velocity forced flows cannot normally be studied, because of the onset of mixed convection. By removing buoyancy, the roles of these forces and flows may be observed and compared with theory.

(3) *Gravitational settling or sedimentation is nearly eliminated.* Unconstrained suspensions of fuel droplets or particles may be created and sustained in a quiescent environment, eliminating the need for mechanical supports, levitators, or stirring devices and enabling a high degree of symmetry and/or quiescence.

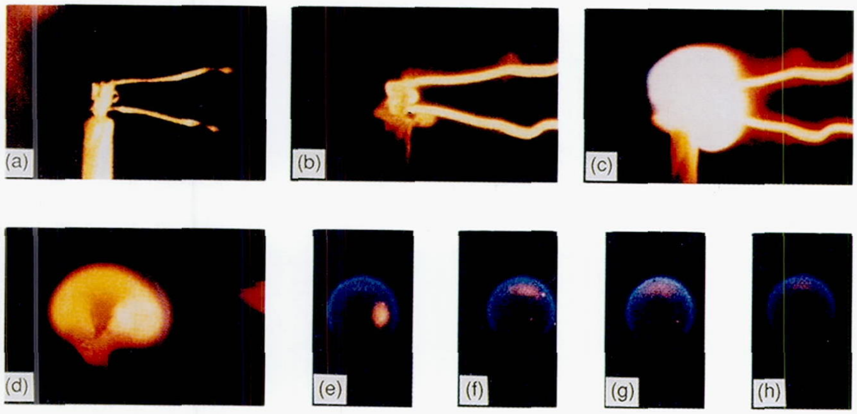
(4) *Larger time or length scales in experiments become permissible.* To limit buoyancy effects in normal-gravity experiments, the size or duration of tests is often constrained. Microgravity permits larger scale experiments which, in turn, allow more detailed diagnostic probing and observation. Microgravity also enables new tests of similitude through experiment.

Combustion experiment programs in drop towers and aircraft have now been completed, and several experiments have been flown successfully on the Shuttle. In addition to new examinations of classical problems, current areas of interest include soot formation and weak turbulence, as influenced by gravity. As will be discussed, unexpected phenomena have been observed—with surprising frequency—in microgravity combustion experiments, raising questions about the accuracy and completeness of our understanding of and about our ability to estimate spacecraft fire hazards.

The interest in microgravity combustion science is not strictly academic. Four internal near-fire incidents have occurred during Shuttle flights. These incidents were caused by overheating of wire insulation and electrical components due to localized loss of cooling air or by electrical short circuits. In each case the crewmembers observed

the evolution of particles and odors and prevented the fire by de-energizing the appropriate circuits; they did not need to discharge fire extinguishers. In a severe incident aboard Soviet Salyut 7, the crew had to discharge an extinguisher, and the uninhabited cabin atmosphere was later vented to the vacuum of space. The atmosphere of the space station was then replenished by stores from a supply flight. These experiences demonstrate that present spacecraft fire-protection practices can respond to a variety of in-flight incidents. Nevertheless, there is growing appre-ciation of the need for fundamental research and technology development with the longer-term objective of investigat-ing and improving spacecraft fire-safety practices.

Several reviews of microgravity combustion science have recently appeared (see the bibliography). In 1989 the microgravity combustion group at the Lewis Research Center published an overview of its pro-gram (NASA TM–101424). That docu-ment briefly described combustion research results, reduced-gravity test facilities, and plans for experimental capabilities in the space station era. The present overview updates our 1989 publication and provides, we hope, a further glimpse into the promise of microgravity combustion research.




A candle flame is often used to illustrate the complicated physico-chemical processes of combustion. The flame surface itself represents the location where fuel vapor and oxygen mix at high temperature and react exothermically. Heat from the flame melts the wax (typically a $C_{20}$ to $C_{35}$ hydrocarbon) at the candle base. The liquid wax rises by capillary action up the wick, bringing it closer to the heat of the flame. This close proximity causes the liquid wax to vaporize. The wax vapors then migrate toward the flame surface, breaking down into smaller hydrocarbons enroute. Oxygen from the general atmosphere migrates toward the flame surface also by diffusion and convection. The survival and location of the flame surface is determined by the requirement that all these processes balance continuously.

In normal gravity, buoyant convection develops due to the hot, less dense combustion products. This has several effects: (1) The hot products are carried away by buoyancy and fresh oxygen is carried toward the flame zone. (2) Solid particles of soot form in the region between the flame and the wick and are convected upward, where they burn off, yielding the bright yellow tip of the flame. (3) Overcoming the loss of heat due to buoyancy, the flame anchors itself close to the wick. (4) The combination of these effects causes the flame to be shaped like a tear drop.

In the absence of buoyant convection, as in microgravity, the supply of oxygen and fuel vapor to the flame is controlled by the much slower process of molecular diffusion. There being no "up" or "down", the flame tends toward sphericity. Heat lost to the top of the candle causes the base of the flame to be quenched, and only a portion of the sphere is seen. The diminished supply of oxygen and fuel causes the flame temperature to be lowered to the point that little or no soot forms, as evidenced by the all-blue flame. It also causes the flame to anchor far from the wick, so that the burning rate, i.e., the amount of wax consumed per unit time, is reduced.

These pictures of the candle flame were developed from 5-sec drop tests conducted in the Lewis Zero Gravity Facility. (a),(b) An electrically heated wire was used to ignite the candle, and then (c) withdrawn 1-sec into the drop. The flame stabilizes quickly thereafter, and its shape appears to be constant for the remainder of the microgravity test (e) to (h).

# REDUCED-GRAVITY FACILITIES

As shown in figure 1, several test facilities provide a free-fall or semi-free-fall condition where the force of gravity is offset by linear acceleration, thus enabling a reduced-gravity environment for scien-tific studies. The facilities have different capabilities and characteris-tics, which must be considered by an investigator when selecting the one best suited to a particular experiment.

To date, most combustion studies have been conducted in the NASA Lewis Research Center's two drop towers and in the model 25 Learjet. The 2.2-Second Drop Tower (see fig. 2), as the name implies, provides 2.2 sec of reduced-gravity test time for experiment packages

with up to 150 kg of hardware mass. The drop area is 27 m tall (The distance through which an experiment package actually falls is 24 m.) with a cross section of 1.5 by 2.75 m. The experiment package, an example of which is shown in figure 3, is enclosed in a drag shield, which has a high ratio of mass to frontal area and a low drag coefficient. The drag shield and experiment assembly is hoisted to the top of the building and suspended there by a highly stressed music wire, which is attached to the release system. A drop is initiated when a pneumatic system notches the wire, causing it to fail. As the drag shield/experiment system falls, the experimental apparatus is free to move within the drag shield. The only external force acting on the freely falling experiment package is the air drag associated with the relative motion of the package within the drag shield. Although the reduced-gravity time is only 2.2 sec, the facility offers both low cost and rapid turnaround time between experiments. It is often used for proof-of-concept or precursor experiments.

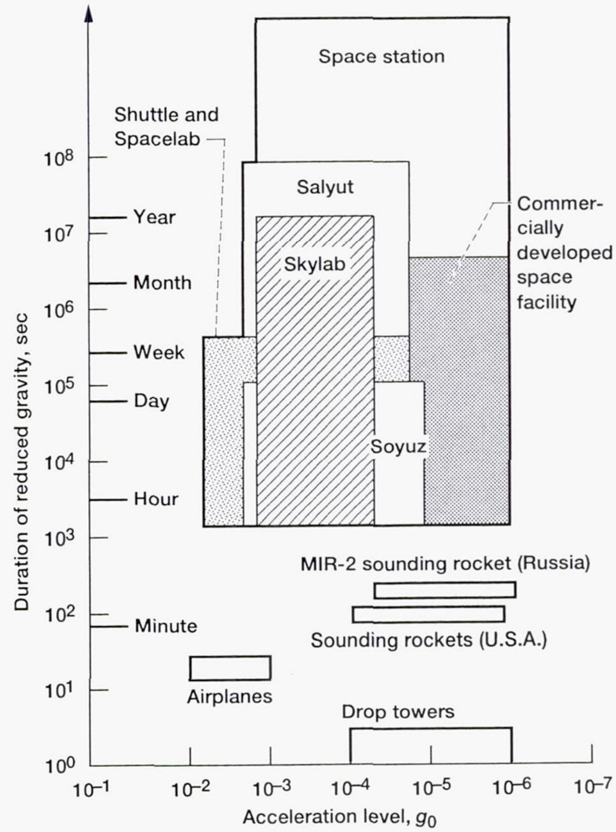



Figure 1.—Characteristic times and acceleration levels of reduced-gravity laboratory facilities.

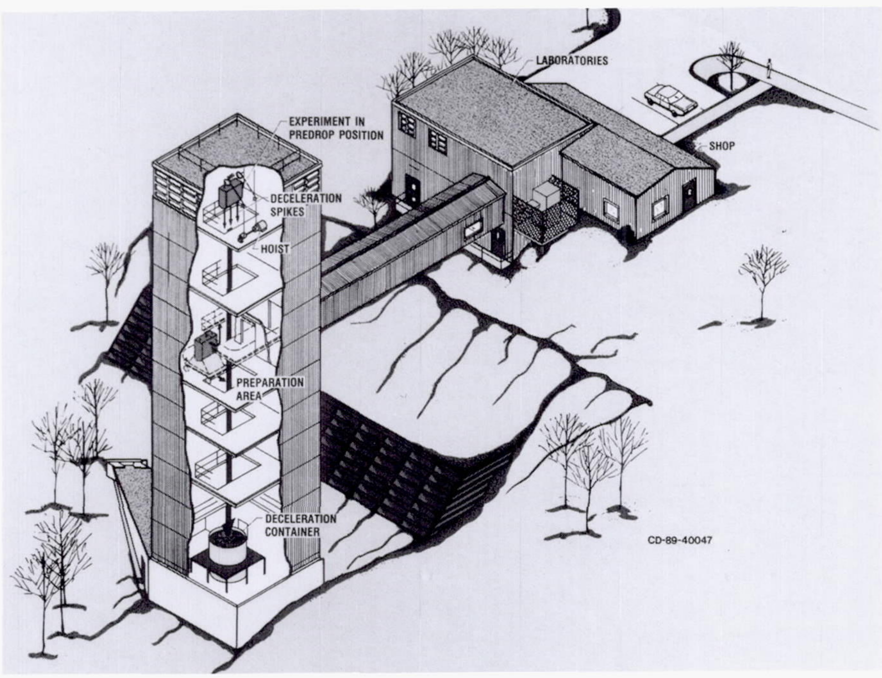



Figure 2.—2.2-Second Drop Tower at NASA Lewis.

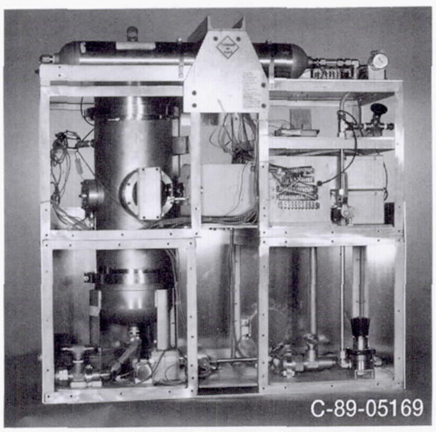



Figure 3.—2.2-Second Drop Tower experiment package (combustion tunnel).

The 5.18-sec Zero-Gravity Facility with its 132-m free-fall distance in an evacuated drop chamber represents a significant expansion in experiment sophistication and research capabilities when compared with the 2.2-Second Drop Tower. A schematic of this facility is shown in figure 4. The Zero-Gravity Facility houses a 6.1-m-diameter steel-walled vacuum chamber that is 145 m deep with a 132-m drop distance. That distance provides 5.18 sec of free fall during which accelerations of about $10^{-6}g$ are attained. Experiments of up to 450 kg in mass are mounted in a 1-m-diameter drop bus as shown in figure 5. The entire chamber is evacuated by a series of pumpdown procedures to a final pressure of $10^{-2}$ torr. Experiment entry into microgravity is initiated by shearing a bolt in the release mechanism. The bus falls free of drag in the near vacuum and is decelerated in a 6.1-m-deep container of small pellets of expanded polystyrene. In addition to onboard data acquisition, data can be transmitted via telemetry during the experiment, allowing the researcher to monitor the progress of the experiment in real time.

Specially modified jet aircraft flying parabolic (Keplerian) trajectories can provide significantly longer reduced-gravity experiment time than can drop towers but not without the penalty of higher gravity levels. For an experiment fixed to the body of an aircraft, accelerations in the range of $10^{-2}g$ can be obtained for up to 20 sec. During one flight, several trajectories are possible. While aircraft may not offer true microgravity, they do offer the significant advantages of permitting researchers to monitor their experiments in real time, to reconfigure them between trajectories, and to use delicate instrumentation precluded in drop tower tests because of severe shock loadings at the end of a

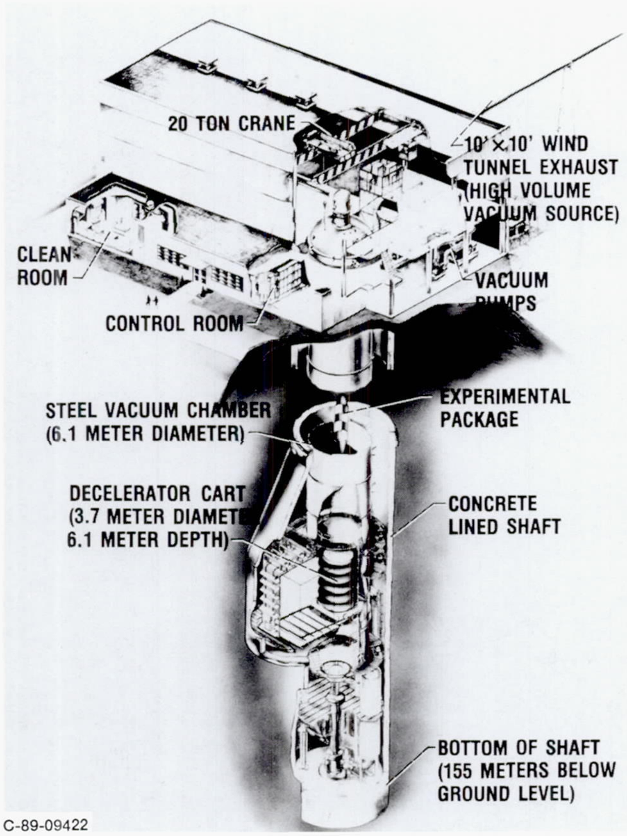



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Figure 4.—5.18-Second Zero-Gravity Facility at NASA Lewis.

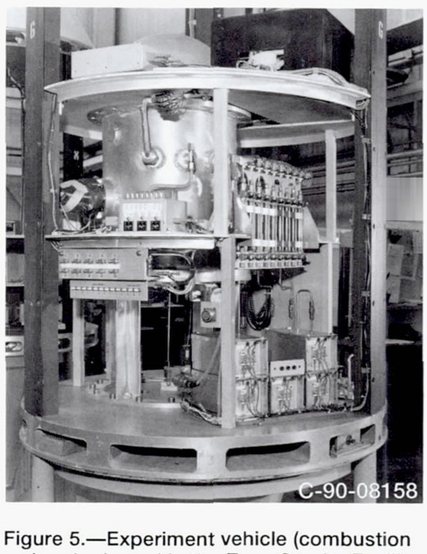



Figure 5.—Experiment vehicle (combustion chamber) used in the Zero-Gravity Facility.

drop. The NASA Lewis Learjet model 25 is shown in figure 6 along with the flight profile of a reduced-gravity trajectory.

Approximately 1.8 m of cabin length are available for experiment mounting and researcher seating. Inherent engine lubrication limitations of this aircraft permit a maximum of six trajectories per flight. Intermediate acceleration levels of 1/20, 1/10, 1/6 (Lunar gravity), 1/5, 1/4, 1/3 (Martian gravity), 1/2, and 3/4 of Earth's gravity can also be achieved in this aircraft.

NASA's KC-135 aircraft (fig. 7), at the Johnson Space Center, operates in a similar fashion to the Learjet when flying experiments fixed to the aircraft body, but, because of its larger size, it also permits free-floated experiments and thus achieves acceleration levels in the range of $10^{-4}g$ for 5 to 10 sec. Up to 60 trajectories can be performed in a single flight. Both the European Space Agency and NASA have sponsored combustion experiments in this facility, and the use of this aircraft is increasing.

Although they have not yet been used in the U.S. microgravity combustion program, sounding rockets can provide a reduced-gravity environment of $10^{-4}g$ for about 300 to 1000 sec. At Lewis their use will be considered for future experiments that may require a compatible time and gravity level but do not require direct observation and operation by a researcher.

Truly long-duration reduced-gravity combustion experiments require space-based laboratories such as the Space Shuttle or Space Station *Freedom*. The Shuttle flight duration for science missions is 7 to 13 days. At a fundamental level, the combined aerodynamic and gravity gradient forces aboard the Shuttle provide a background acceleration level of around $10^{-4}g$. Crew motion, which is the most significant disturbance, can induce accelerations in the range of $10^{-3}g$.

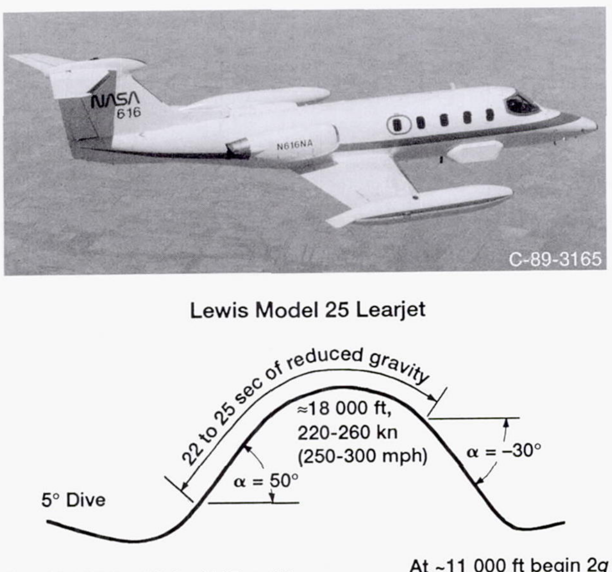



Figure 6.—NASA Lewis airborne low-gravity facility. A typical reduced-gravity trajectory is also shown.

Figure 7.—Experimenters aboard the NASA KC-135 aircraft during a reduced-gravity maneuver.

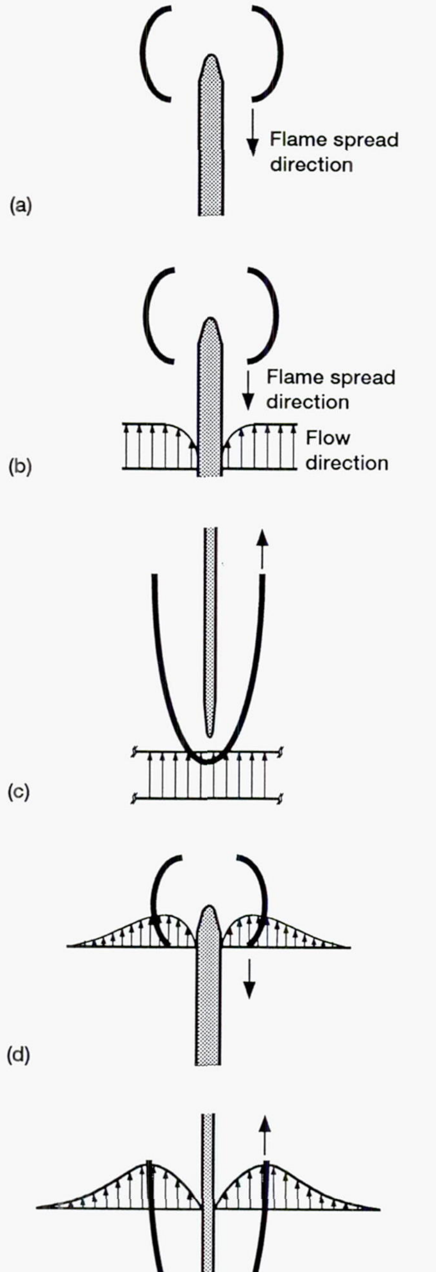



Figure 8.—Flame spread over a solid fuel for different flow configurations: (a) microgravity, quiescent atmosphere, (b) microgravity, forced, opposed flow, (c) microgravity, forced, concurrent flow, (d) normal gravity, buoyant, opposed flow, (e) normal gravity, buoyant, concurrent flow.

Many investigators therefore request that their experiments be operated during periods of reduced crew activity. Upward and downward data communication links are available, when necessary, over the Ku band. Thermal control, physical space availability, and electrical power capability depend on where an experiment is mounted in the Shuttle (e.g., middeck locker or cargo bay) or the type of mission (e.g., Spacelab). Substantial astronaut involvement is not only possible but encouraged for middeck and Spacelab experiments.

In the future, Space Station *Freedom* will provide the highest quality, longest duration reduced-gravity laboratory (see, again, fig. 1). Within its instrument racks will be dedicated space, electrical power, and advanced diagnostic instrumentation for reduced-gravity combustion experiments. Multiple experiments will be conducted in experiment modules by scientific specialists. Principal investigators on Earth will be able to monitor and modify, in real time, the performance of their experiments. This future facility, along with the means by which investigators' experiments will be selected for flight, are discussed later in this document.

# MICROGRAVITY COMBUSTION EXPERIMENTS

In the following sections, a sampling of the findings from microgravity combustion experiments is provided. For a complete listing of ongoing microgravity combustion experiments funded by NASA, see the appendix.

## Solid Materials Flammability

The combustion of solid materials in reduced-gravity environments is a key area of research, not only for improving our fundamental understanding of the mechanisms of solids combustion, but also for improving the fire safety during human spaceflight.

Many processes contribute to the propagation of a flame over a solid fuel. Conduction, convection, and radiation of heat from the flame to the solid fuel and to the environment all play important roles in the balance of heat produced within the flame and of the heat lost to the environment and heat used in vaporizing the solid fuel. Surface pyrolysis of the fuel and gas-phase chemical reactions are both vital processes involved in the production of heat needed to sustain the flame. Species diffusion and convection must also occur so that the appropriate mixture of fuel and oxidizer are present within the reaction zone to allow the reaction to proceed. Additionally, the products of reaction must be removed so that they do not extinguish the flame. With all of these interacting processes involved in flame spread, it is difficult to determine which dominates. By eliminating gravitationally induced buoyant flows and the associated heat and mass transport, other transport processes that cannot be isolated on Earth can be studied directly.

Figure 8 illustrates the importance of gravity and low-speed flows on the burning of a solid fuel. A flame is shown spreading over a thin, solid fuel for five common flow configurations. In a quiescent, microgravity condition, the flame encounters fresh oxidizer as it spreads across the solid (as in fig. 8(a)). If a forced flow is imposed *opposite* the

flame-spread direction, a boundary-layer flow develops along the fuel surface before its encounter with the flame (as in fig. 8(b)). On the other hand, when the direction of the forced flow is *concurrent* with the flame-spread direction, no boundary layer is formed (as in fig. 8(c)). In normal gravity, the large *temperature gradients* across the *downward*-spreading flame cause large density gradients in the gas phase, and, in turn, induce a buoyant flow of gas to oppose the propagating flame. This buoyant flow is depicted in figure 8(d) along with the observed flame shape. For this case and for the cases in figures 8(a) and (b), the flame stabilization zone and the factors influencing the spread rate are primarily at the leading edge of the flame. In a normal-gravity upward-spreading flame (fig. 8(e)), buoyant flow and flame spread occur in the same direction. For this case and for the case in figure 8(c), the flame is stabilized at the trailing edge of the flame, but the rate of spread is strongly influenced by heat transfer from the rest of the flame. It is interesting to note that no solid material has yet been studied for all five of these common flow configurations. In the subsections which follow, our reduced-gravity experiments and our understanding of the results are described according to these flow configurations.

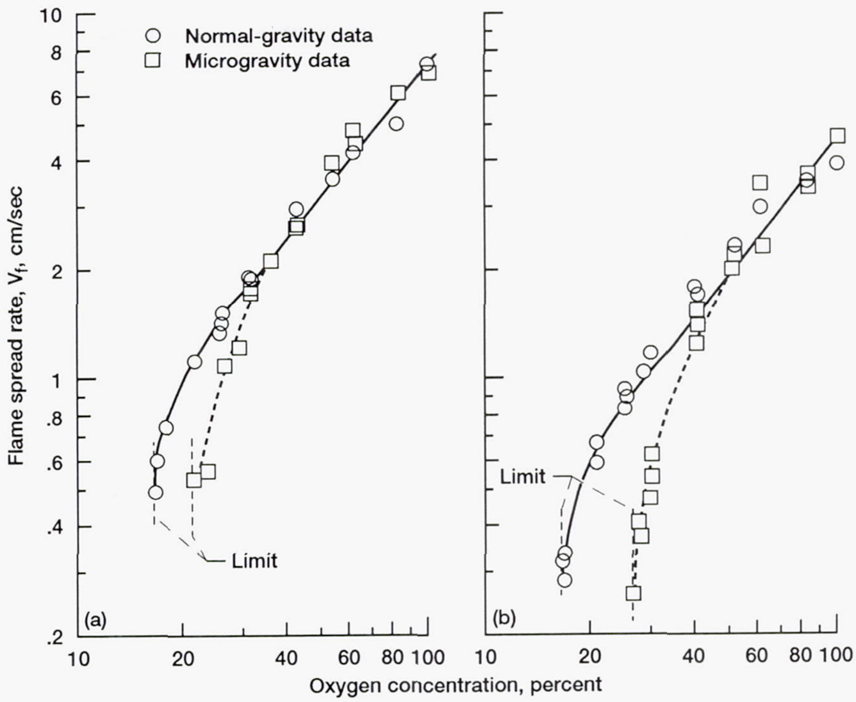



Figure 9.—Normal and microgravity flame spread rates as a function of oxygen concentration for (a) single and (b) double thicknesses of fuel.

**Quiescent environment.**—Experiments with very thin paper fuel samples have been conducted at various oxygen concentrations. The data, plotted in figure 9 for two thicknesses of fuel, reveal that for high oxygen concentrations, the flame-spread rate, $V_f$, is independent of the gravity level; this result is consistent with the so-called "thermal theory" of flame spread, where the flame-spread rate is controlled by gas-phase heat conduction. However, for oxygen concentrations below roughly 40 percent for this fuel, $V_f$ is lower in microgravity than in normal gravity. Also, while in normal gravity the limiting oxygen index[1] (LOI) for the two thicknesses is nearly the same, in microgravity the difference is substantial.

Thermal theory predicts that the ratio of flame-spread rates for the double thickness sample should be twice that of the single thickness sample. This behavior is observed in normal gravity and microgravity, except near the LOI, where the ratio dramatically increases. This near-LOI region is currently being studied, both experimentally and theoretically, to ascertain the mechanisms of flame spread and extinction there. The normal-gravity flame is extinguished by blowoff at low

[1]The LOI for a material is defined as the lowest oxygen concentration in which the material's burning is self-sustained, i.e., in which a flame will self-propagate without heat from an external source.

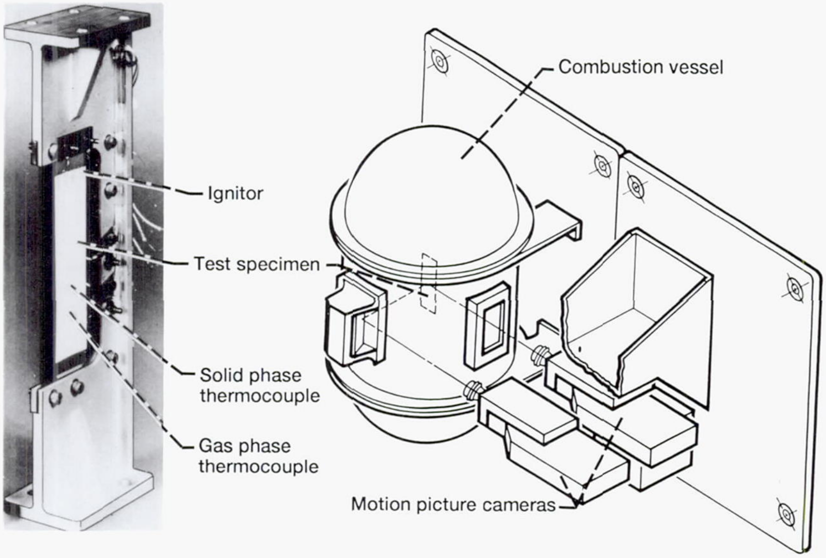



Figure 10.—Space Shuttle flight hardware for the solid surface combustion experiment.

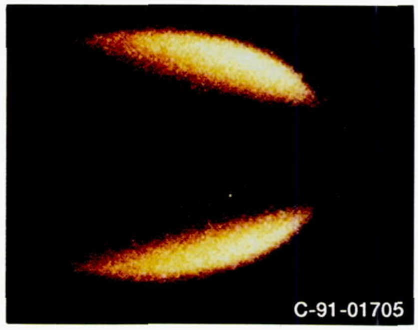



Figure 11.—Flame spread over an ashless filter paper sample in a 50 percent oxygen-50 percent nitrogen environment at 1.5 atm. The experiment was conducted aboard the Space Shuttle in the SSCE apparatus. This view is slightly larger than the actual size of the flame.

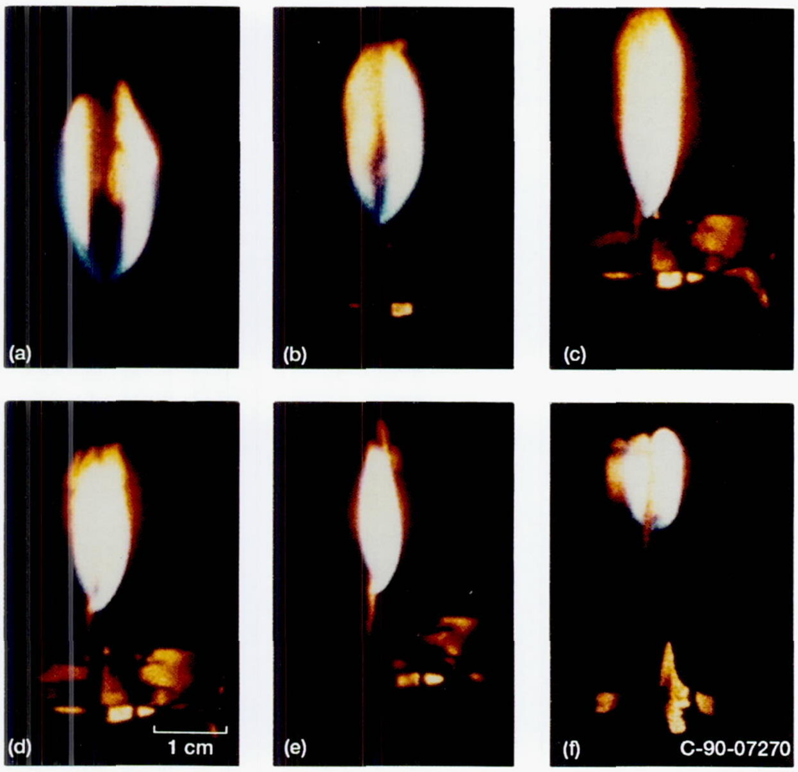



Figure 12.—Flames over paper samples for different opposed flow velocities of (a) 5 cm/sec, (b) 10 cm/sec, (c) 15 cm/sec, (d) 20 cm/sec, and (e) 30 cm/sec at reduced gravity and (f) buoyantly induced flow at normal gravity.

Damkohler number[2], where the residence time of fuel in the reaction zone is much shorter than the chemical reaction time. However, in microgravity, the fuel residence time is long, so extinction must be due to some other mechanism.

In order to study thicker solid materials, longer microgravity times than are available in ground-based facilities are necessary. The solid-surface combustion experiment (SSCE) was flown on the Shuttle three times in 1990 and 1991. (The flight hardware is shown in fig. 10.) During these flights, ashless filter paper fuel samples were burned in a quiescent, reduced-gravity environment to determine the effects of gravity, oxygen concentration, and pressure on the burning process. The flame shape and spread rate were captured on color motion-picture film (see fig. 11), and flame and pyrolysis temperatures and pressure rise in the chamber were also recorded. Comparisons of these early results with existing fuel-pyrolysis models suggest that, while the simple models adequately predict flame spread in normal gravity, more complex pyrolysis models are needed to predict flame shape and fuel burnout in microgravity. Eight flights in all are currently planned for the SSCE to study both paper and polymethylmethacrylate (PMMA) fuels in quiescent, microgavity environments.

Other quiescent experiments, these conducted in a drop tower, varied oxygen concentration and diluent ($CO_2$, He, Ar, or $N_2$). The

[2]The Damkohler number is defined as the ratio of the time of the fuel's and oxygen's residence in the reaction zone to the time required for their chemical reaction.

extinction efficiency of a diluent is determined by the oxygen concentration that will no longer support a flame. The higher the LOI, the more efficient the diluent in extinguishing the flame. Of the diluents tested, carbon dioxide is the most efficient extinguisher because of its strong gas-phase radiative characteristics and its high heat capacity, both of which are net heat losses for weak flames near the LOI. Helium is also efficient because of its high thermal diffusivity, which yields high conductive heat losses. Argon, which has the same thermal diffusivity as nitrogen, is least efficient because of its lower heat capacity and lower thermal conductivity.

**Opposed-flow flame spread.**—Drop tower experiments with very thin paper samples revealed a strong effect of very low-velocity flows on flame spread. The opposed-flow velocities studied were below those obtainable in normal gravity where buoyancy naturally induces higher-velocity flow. Figure 12 shows six flames spreading over paper samples in air at various flow velocities. For velocities below 5 cm/sec (not shown in the figure), the flame leading edge is diffuse blue, the flame tail is open, and a large fuel-rich dark zone exists between the visible flame and the fuel surface (fig. 12(a)). At higher velocities, the flame moves closer to the fuel surface, decreases its width (figs. 12(b) to (e)), and increases its temperature as evidenced by soot production.

Flame-spread rates at various gravity levels and forced-flow rates are plotted in figure 13 for three ambient oxygen concentrations. The characteristic relative velocity, $V_{cr}$, is the sum of $V_f$ and the (generally predominant) forced or buoyantly induced oxidizer flow. Again, low-speed flows over these samples, that is, at $V_{cr} < 30$ cm/sec, can only be obtained in reduced gravity. A nonmonotonic dependence of $V_f$ on $V_{cr}$ is noted at all three oxygen concentrations, suggesting that different mechanisms control the rate of spread at low and high $V_{cr}$. The highest $V_f$ is observed in microgravity, where $V_f$ increases sharply with increasing $V_{cr}$ to a maximum at $V_{cr}$ = 15 to 20 cm/sec. At 30 percent oxygen and above, $V_f$ becomes independent of opposed-flow velocity over a wide range of $V_{cr}$.

Similar to the flame-spread trends, the observed preheat and flame lengths were nonmonotonic, with the maximum flame lengths corresponding to the maximum flame-spread rate. For low velocities the flame tail opened, and solid-phase temperature data indicated that pyrolysis lengths increase dramatically with decreasing opposed-flow velocities; that is, not all of the fuel is consumed for these weakest flames, but rather a substantial char remains even for the very thin fuel used in these experiments. Such behavior was unanticipated by existing theory.

Based on both the quiescent and opposed-flow results, a flame-spread map (depicted in fig. 14) has been hypothesized. For the conditions below the solid curve, a flame cannot be sustained. For the conditions above the solid curve, the map depicts three distinct regions where different mechanisms control flame spread in an opposed-flow environment. In region I flame spread is controlled by gas-phase conduction and is adequately described by existing "thermal" theories. In region II existing theory adequately predicts that high opposed-flow velocities impose fuel residence-time limitations on the flame-spread process. In region III, obtainable only in microgravity, a new controlling mechanism of flame spread has been suggested: the rate of oxidizer transport to the reaction zone is so slow that it may be the controlling,

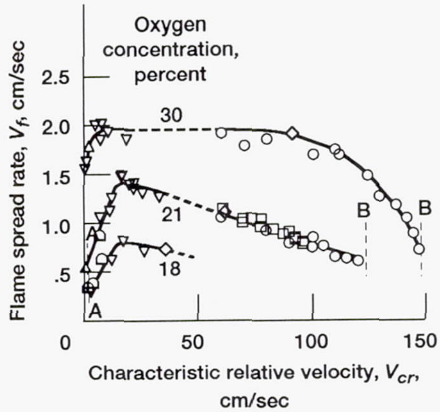



Figure 13.—Flame spread rates at three oxygen concentrations as function of characteristic relative velocity. To the left of line A is the quench extinction region; to the right of lines B is blow-off extinction region.

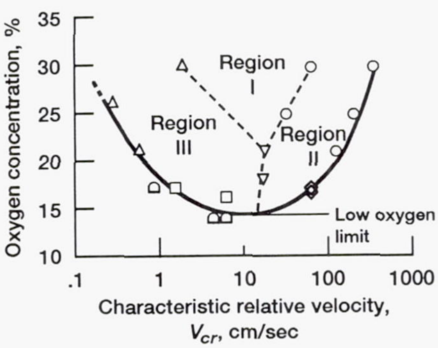



Figure 14.—Map of the controlling mechanisms of flame spread as function of oxygen percentage and characteristic relative velocity for a thermally thin fuel.

or limiting, factor that reduces chemical reaction and heat generation rates and, when combined with ongoing heat losses, the flame-spread rate.

An alternative hypothesis for region III is founded on the roles of surface and gas-phase radiation. For quiescent flame spread in microgravity, the rate of spread correlates with Damkohler number. Supercomputer-based numerical models have shown that calculations performed with surface radiation alone and those performed with surface and gas-phase radiation demonstrate similar spread-rate trends; however, the flame structures are quite different—with gas-phase radiative losses producing cooler, smaller flames. Thus, while the flame is cooled due to gas radiation, some of this radiation is incident on the solid and can enhance the rate of the flame's spread. The effects of surface radiation become important only at low $V_{cr}$ when the radiative loss becomes a significant portion of the combustion heat release. These radiative heat losses from the fuel surface, which can quench the flame, have been proposed as the extinction mechanism at the LOI in microgravity.

The point at which the two extinction boundaries meet in figure 14 defines a low oxygen limit for flammability. At oxygen concentrations below this limit, the material will not burn, regardless of the opposed-flow velocity over the sample. This occurs at roughly the flow velocities produced by a spacecraft's ventilation system. Also shown in the figure is a dashed, near-vertical line dividing regions II and III at $V_{cr}$ = 10 to 20 cm/sec. This line defines conditions that result in maximum flammability both in terms of peak flame-spread rate and minimum oxygen concentration supporting stable burning.

A new Shuttle-based experiment, called the DARTFire (diffusive and radiative transport in fires) experiment, is being developed. The objective of DARTFire is to obtain a better definition of the roles of fuel thickness, radiation, thermal transport, and oxygen mass transport in region III (of fig.14). Various thicknesses of acrylic material will be burned over a range of oxygen concentrations and opposed-flow velocities in different diluents. In a novel approach, the net radiative field will be varied by a spot heater or by a heated shroud around the sample.

**Concurrent-flow flame spread.**—In normal gravity upward-spreading flames are larger than downward-spreading flames, and the LOI is smaller—principally because of the different spreading mechanisms. In upward-spreading flames, before the fuel burns through, the flame base remains stationary while the tip spreads upward, lengthening the flame. For a thin fuel, the upward-spreading flame can, in principle, reach a limiting size if the spread rate becomes equal to the fuel-burnout rate at the flame base. A possible consequence of the large spread rates and sizes of upward-spreading flames is the onset of turbulence in the downstream flame-tip region where spreading occurs.

While laminar flow is generally induced by buoyancy in the downward-spreading flames, turbulent flow may occur in upward spread. Low-speed flows in reduced gravity provide a better chance to observe a lower spread rate and laminar spreading behavior in concurrent flow.

To simulate low-speed flows (0 to 5 cm/sec), a device was developed that translates test specimens through oxidizing atmospheres inside a large combustion chamber integrated into a Zero-Gravity

Facility standard drop bus. Concurrent-flow flame-spreading tests were performed for paper samples translating through oxygen-nitrogen mixtures of 12 to 21 percent oxygen at 1 atm of pressure. Figure 15 shows that the flame base is consistently the brightest part of the flame and that its velocity is steady following an initial transient associated with ignition. The flame tip position fluctuates unsteadily at all test conditions. A linear fit was calculated for the time-varying flame length. Based on the linear fit, all flames were growing or shrinking during the limited test time. It could not be determined whether at longer test times, the growing tip would continue to outdistance the flame base or whether the base would catch the shrinking tip and extinguish the flame. Numerical simulations are being developed to assist in answering these questions.

Increases in flame length in reduced gravity with increases in concurrent-flow velocity differ from the results of similar experiments in normal gravity, but at higher concurrent-flow velocities, in a mixed-convection environment. In those normal-gravity experiments, for increasing concurrent-flow velocities below approximately 100 cm/sec, flame-spread rates increased, and flame lengths decreased. This difference in behavior suggests that the mechanisms controlling flame spread are different in normal and reduced gravity.

Theoretical analyses of both opposed- and concurrent-flow flame spread are being conducted to uncover these differences. Models that include multistep pyrolysis, thermal radiation, and multicomponent diffusive transport are being developed. The effect of gravity and gas-phase radiation on concurrent-flow flame spread will also be studied. A three-dimensional, unsteady model will be developed to examine the effect of flow on flame ignition and growth in microgravity. Finally, flame spread over thicker fuels will be examined.

However, much remains to be learned about solid material flammability in reduced-gravity environments. In particular, methods of determining the reduced-gravity flammability of materials through normal-gravity testing need to be refined so we can identify those materials that pose a fire hazard in space, without being too stringent in limiting the use of materials needed to perform normal operations aboard the spacecraft. It is well accepted that flammability is higher for an upward-spreading flame in normal gravity than either for a downward-spreading flame in normal gravity or for spreading flames in quiescent microgravity. As such, the NASA material selection testing is based on upward spread in normal gravity (the most conservative approach). Experiments will be performed soon to determine flammability with concurrent flow in reduced gravity and to compare those results with upward spread in normal gravity. When such studies are complete, the degree of conservatism of the material selection testing may be more easily estimated. More information on flammability testing is provided in the Spacecraft Fire Safety section later in this document.

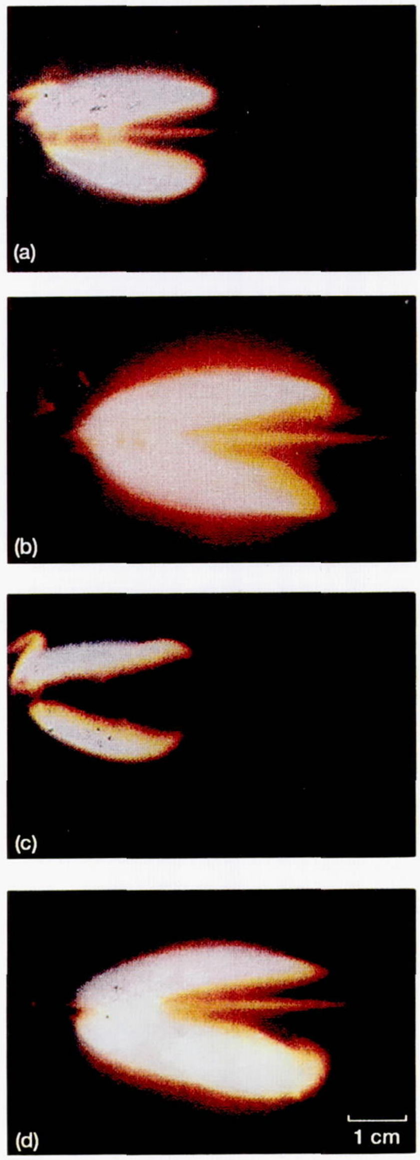



Figure 15.—Forced, concurrent flow spread over paper samples in microgravity for different oxygen concentrations and flow velocities: (a) 25.9 percent $O_2$, $U$ = 5 cm/sec; (b) 25.9 percent $O_2$, $U$ = 10 cm/sec; (c) 21 percent $O_2$, $U$ = 5 cm/sec; and (d) 21 percent $O_2$, $U$ = 10 cm/sec.

## Smoldering Combustion

Smolder is a nonflaming combustion process that takes place in porous combustible materials and is characterized by a heterogeneous surface reaction that propagates through the material. It is of interest both as a fundamental combustion problem and as an important fire


Figure 16.—Smoldering combustion experiment hardware (a) for the Space Shuttle glovebox (b). The glovebox facility provides a photographic laboratory and ergonomic work area that allows Shuttle crew members to carry out experiments or operations using small quantities of toxic, irritant, or potentially infective materials that might contaminate the Spacelab atmosphere. The glovebox was designed to handle fluid, materials science, and combustion experiments. Here, astronaut Carl Meade (left) and NASA Lewis scientist Alex Pline check the operation of a glovebox payload for the USML-1 mission.

risk since fires are often triggered by the transition from smolder to rapid flaming. The transport and reaction mechanisms that sustain smolder are complex, and the removal of gravity substantially simplifies its study. Furthermore, the predicted behavior of smoldering combustion in a space-based environment is today completely unverified.

Normal-gravity experiments with cellulose and polyurethane foam have examined smolder-front propagation in quiescent environments and in flowing environments for different magnitudes and directions of forced oxidizer flow. Early tests with packed cellulose revealed only very limited effects of gravity, in part because of the low permeability of the packed cellulose and in part because material settling makes it impossible to conduct upward-smolder experiments with packed cellulose. Later tests used polyurethane foam to study upward smolder.

Extensive normal-gravity foam smolder experiments have allowed us to characterize the propagation of a smolder front from the ignitor surface through a foam sample into three regions. The first region is largely dominated by the ignitor. In the second zone, outside influence of the ignitor, sustained smolder propagation is evident. In the third region, where the front approaches the end of the fuel sample, buoyant transport dominates other processes, and the sample typically undergoes transition to flaming in the upward-spreading case and in many downward-spreading cases, as well. In upward-propagating smolder the transition to flaming occurs above the smolder front. Whereas, in downward-propagating smolder, the transition to flaming usually occurs as a secondary reaction in the char zone above the smolder front. This occurs because, as the front reaches the end of the sample, additional oxygen reaches the hot char zone, providing the conditions needed for ignition of the char.

Reduced-gravity tests have been conducted in drop towers and on the NASA KC-135 aircraft. In these experiments the sample was ignited in normal gravity, and the transient response of the smolder front to the acceleration trends was observed. Strong buoyancy effects were evident in the equivalents of zones 1 and 2 of the smolder process. The transition to reduced gravity caused the temperature gradients (with respect to time) in the sample to reverse. This effect was seen in both upward- and downward-propagating smolder experiments on the KC-135. It was impossible to maintain a sustained smolder front under these conditions since the smolder front would ultimately be bordered by pyrolized fuel on both the upstream and downstream faces and extinguishment would result due to lack of fuel in the vicinity of the front.

Based on these efforts, it has been shown that the study of steady smoldering requires periods of time that can only be achieved in space. The first space-based smoldering combustion experiments will be conducted on the USML–1 Space Shuttle mission, scheduled for mid-1992, inside a general-purpose glovebox (fig. 16). Cylindrical samples (8 cm long, 5 cm in diameter) of open-cell polyurethane foam will be used as the fuel. Each test will be conducted in a separate, sealed, Lexan or polycarbonate box (fig. 16(a)) placed inside the glovebox. The data collection will include a video record and thermocouple measurements made at eight locations in the foam.

Smoldering will be initiated in a manner similar to the ground-based work, using a resistively heated ceramic element. Two ignitor geometries will be used: (1) an axial ignitor for the study of radial smolder-front propagation, and (2) an end-plate ignitor for the study of

axial front propagation. Two tests will be conducted for each ignitor geometry using quiescent and forced flow, respectively. In the forced-flow tests, a weak coaxial flow will be generated around the sample using a small fan. The air velocity induced by the fan will be significantly less than that caused by natural convection in normal gravity and will be of the order of the flows caused by the ventilation systems on the Space Shuttle.

Other hardware for space experiments is being developed for smolder investigations to be conducted in three stages. Phase I will consist of quiescent experiments in which the axial smolder-front propagation will be observed under various oxidizer concentrations. Phase II will consist of forced-flow experiments in which the smolder-front propagation will be observed under various gas flow rates. Half of the phase II experiments will study behavior in concurrent-flow conditions and half in opposed-flow. Phase III will study the transition to flaming in an experiment in which oxidizer will flow over an exposed surface of the smoldering foam. The oxidizer flow conditions will be varied, and the effect of the flow on the transition to flaming will be observed.

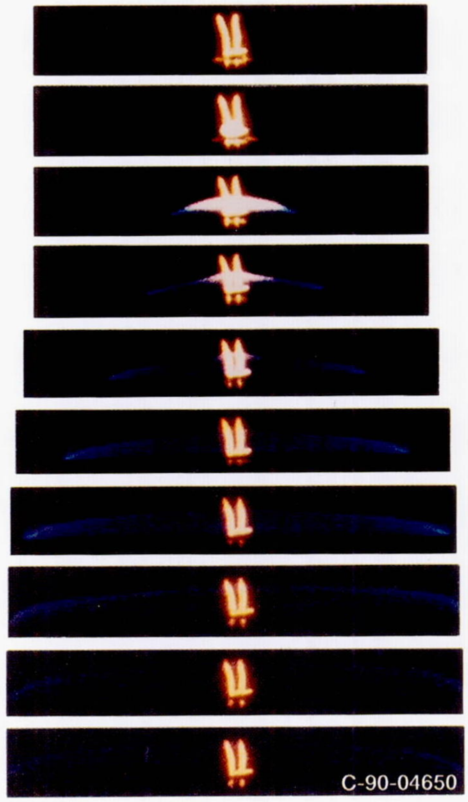


Figure 17.—Microgravity flame spread over liquid fuel pools. Time between frames, 0.12 sec.

## Flame Spread Across Pools of Liquid Fuels

In order for ignition to occur in a liquid pool of fuel that is below its flash point temperature, a heat source must provide sufficient energy to preheat and vaporize the fuel to a combustible composition. After ignition, the flame itself must provide the energy for preheat and vaporization for the flame to spread. To this extent, flame spread over liquid pools is similar to flame spread over solids. However, unlike solids, in the presence of a heat source, convection will develop in the liquid, driven by both temperature-induced surface tension gradients and by buoyancy. Gas-phase motion is determined both by buoyant forces and by the "no-slip" condition at the interface between the liquid and the gas. Therefore, gravity affects the liquid fuel and gas-phase motions and, as such, influences the supply of oxidizer and heat transfer ahead of the flame. This process is so complex that it is not clear, a priori, whether the time to ignition and flame-spread rate will be faster or slower in reduced gravity than in normal gravity.

Also unlike solids, flame spread in normal gravity may become unsteady, pulsating at a regular frequency. The cause and phenomenology of pulsating flame spread are not completely understood. In particular, the role of buoyancy is unclear. Experiments of flame spread over shallow pools of alcohol fuels (see fig. 17) have been conducted in the Zero-Gravity Facility. Results showed that, independent of oxygen concentration, alcohol fuel, and diluent type, microgravity extinction coincided with the onset of conditions for pulsating spread in normal gravity. This suggests that gas-phase flow, naturally induced by buoyancy forces in normal gravity, is a requirement for pulsating spread. On the other hand, microgravity flame-spread rates were nearly identical to corresponding normal-gravity flames for conditions where the normal-gravity flames spread uniformly. This similarity indicates that, in both conditions, buoyancy-related convection does not affect flame spread, at least for the physical scale of the experiments. When the atmospheric nitrogen was replaced with argon, the conditions for the onset of normal-gravity pulsating flame spread and

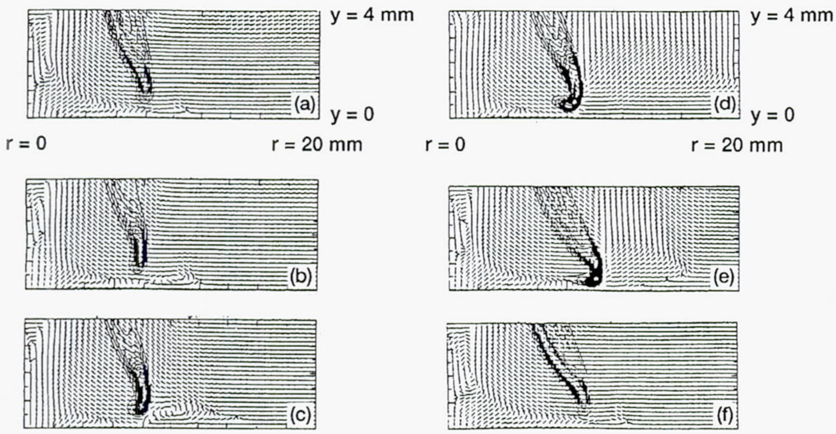



Figure 18.—Flow pattern and flame structure for one flame pulsation at normal gravity. In (d)-(f), the recirculation cell structure in front of the flame leading edge is destroyed during the premixed burning portion of the flame. Hot gas expansion opposes the flow of fresh oxygen to the reaction zone, and the flame moves backwards (as if it were being extinguished). The gas expansion rate decreases after the flame propagates through the premixed region, and, subsequently, the buoyant forces recover to provide fresh oxygen to the reaction zone.

microgravity flame extinction were changed, in agreement with the expected lowering of the flash point through the thermal properties of the diluent. Helium-diluted flames, however, showed unexpected results with a shift to apparently higher flash-point temperatures and high normal-gravity pulsation amplitudes.

Historically, modeling of flame-spread required an assumption of the flame-spread rate in order to determine the flow and temperature fields ahead of the flame. The prediction of ignition, flame-spread rates, and the flow and temperature fields has only recently been accomplished on supercomputers. It is predicted that, with a hot-wire source near the fuel surface, ignition occurs sooner in reduced gravity for pools of $n$-decane in air. This is due to the direction of the convection of heat from a hot source: in reduced gravity the flow is downward toward the pool, whereas in normal gravity it is upward. After ignition, both uniform and pulsating spread, depending on the gravity level and initial pool temperature, have been predicted. Figure 18 shows the predicted pulsating flame position and gas-phase flow field as a function of time in normal gravity.

Plans are to extend microgravity experiments, both numerical and experimental, to deeper pools in order to investigate the potential effects of liquid-phase buoyancy. Also, the effects of opposed and concurrent airflow on flammability and flame-spread characteristics will be examined. It is hoped that these tests will determine whether pulsating spread can occur in microgravity in the presence of a steady forced flow.

## Premixed Gas Combustion

Gravity affects premixed gas flames through buoyancy-driven convection. This effect is generally small except in mixtures with low burning velocities. In most fuel-air mixtures burning in normal gravity, this condition corresponds to mixture compositions far from stoichiometric. When the mixture is sufficiently fuel-lean or fuel-rich, buoyancy effects become apparent. Buoyant convection affects the rate of transport of thermal energy and chemical species within the combustible mixture and the rate of heat losses from the system to the surroundings. The rate of heat loss, in turn, influences the flame shape and burning rate, as

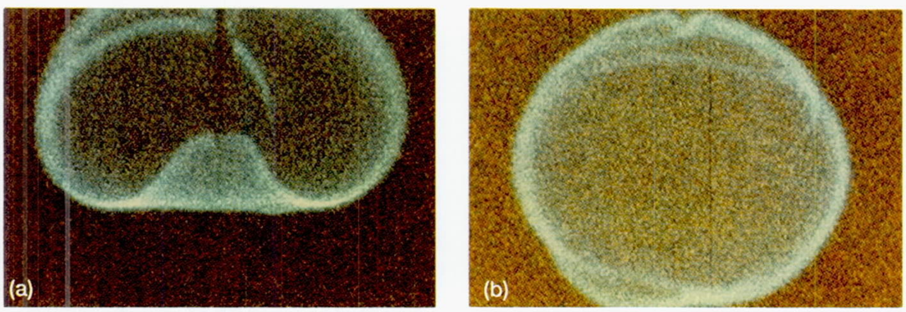



Figure 19.—Effect of gravity on premixed gas flames. In each photograph a spark has ignited the fuel in a pressure vessel (0.25 $m^3$ volume) filled with a 5.5 percent methane and air mixture. Initial temperature and pressure are 23 °C and 1 atm. Photographed 0.25 sec after ignition. (a) In normal gravity, the flame has a hemispherical shape due to buoyancy. (b) In reduced gravity the flame shape is spherical. The small deformations are due to heat loss to the spark electrode used for ignition.

displayed in figure 19. In microgravity, flames ignited by a spark in the center of a constant-volume vessel propagate in a slow, spherical fashion because of the reduction of buoyancy.

The most limiting mixture compositions (e.g., most fuel-lean, most fuel-rich, or most dilute with inert material) that can sustain flame propagation are called flammability limits. Despite decades of study, the mechanisms of flammability limits are not well understood. Many have been proposed, including conductive and/or radiative heat losses, flame curvature effects, fuel chemistry, and buoyancy. Previous investigations suggested buoyant convection as the dominant contributor to these mechanisms under normal gravity conditions. Recent microgravity studies, both theoretical and experimental, verified this suggestion, finding, among other things, wider limits in microgravity than in upward-propagating flames in normal gravity. Furthermore, the properties of these limits were very different from those observed in normal gravity. Instead of buoyancy causing the limits in normal gravity, radiative heat losses from the hot combustion gases are often the primary factor leading to flame extinguishment in microgravity.

A new mode of unstable flame propagation, called a self-extinguishing flame (SEF), is observed for some mixtures whose compositions are outside the flammability limits. An SEF propagates a substantial distance from the ignition point but extinguishes before nearing the walls of the pressure vessel. As opposed to a simple, failed ignition, the energy release before extinguishment is orders of magnitude larger than the ignition source energy. The SEF behavior has only been observed in microgravity and for mixtures whose Lewis number[3] (Le) is less than 1. Theory proposes that SEF's result from the greater resistance of curved flame fronts, as opposed to planar fronts, to extinguishment by heat losses and from the unequal diffusion of thermal energy and reactants. Computations of the dynamics of SEF's agree with experimental observations except for rich propane and air mixtures, where the evolution time is much longer than the theoretical prediction. It is possible that these slowly evolving structures would extinguish if more microgravity time were available. Also, superadiabatic flame front temperatures occur in the propane and air mixtures, but not in other SEF flames. Questions remain whether the long evolution time represents conventional SEF behavior or a new phenomenon that appears at early times to be SEF-like.

For mixtures with sufficiently low Le, propagating, but discontinuous, cellular flame structures have been observed. Several mechanisms have been identified that could lead to the formation of cellular structures. These include preferential diffusion of one reactant, diffusional-thermal instability, hydrodynamic instability, heat loss, and buoyancy. The interactions of these different mechanisms determine the conditions at which the cellular structures appear. Experimental evidence, along with theory, suggests that diffusional-thermal instability is the dominant mechanism for the onset of cellular flames for hydrogen-oxygen-nitrogen mixtures. For sufficiently reactive mixtures of these constituents, cellular structures split and spawn new cells in regular patterns. However, for less reactive mixtures, cells form shortly after ignition but do not split into new cells. Rather, they evolve into a flame structure composed of stationary, stable, spherical flamelets, termed "flame balls" (as shown in fig. 20). For progressively more dilute

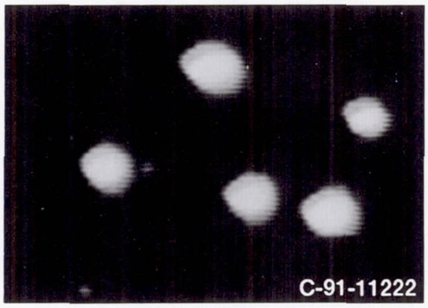



Figure 20.—Effect of low Lewis numbers on premixed gas flames. The cells form shortly after ignition and become stable flame balls. The cells form when a thermal-diffusive instability exists, i.e., when the premixed field of unburnt gas becomes nonuniformly enriched with hydrogen. The gas composition prior to ignition was 5.7 percent hydrogen, 11.3 percent oxygen and 83 percent sulphur hexafluoride. Each flame ball is between 0.5 and 1 cm in diameter.

[3]The Lewis number is defined as the ratio of the thermal diffusivity of the bulk mixture to the mass diffusivity of the stoichiometrically deficient reactant.

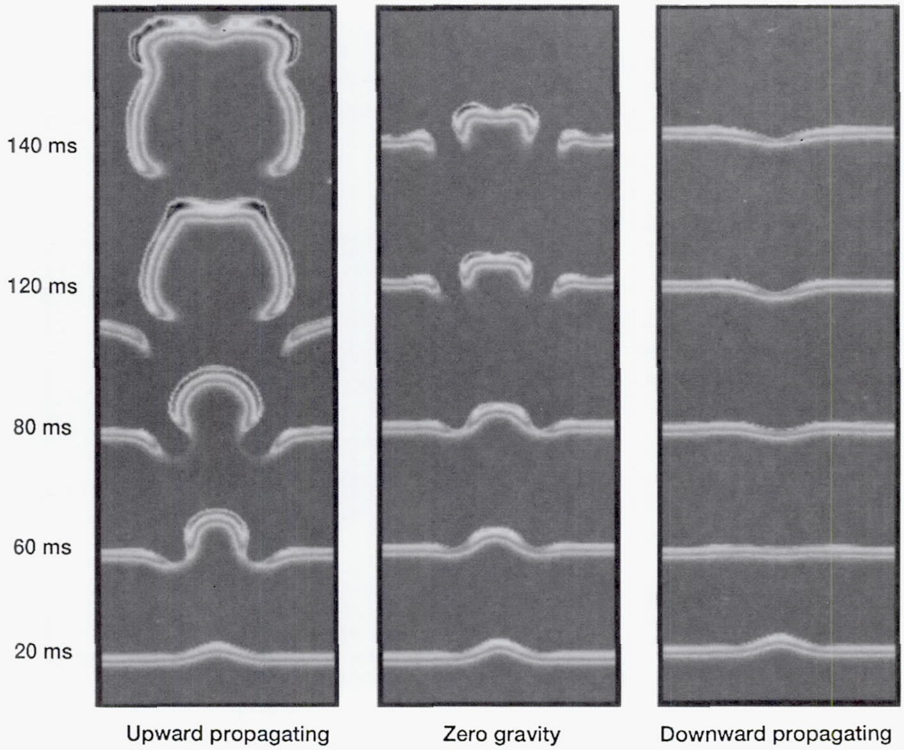



Figure 21.—The effect of gravity on cellular flame formation from an initially perturbed planar flame front has been studied numerically for premixed $H_2/O_2$ flames. Of the three cases shown here, the downward-propagating flame in normal gravity is most stable. For the upward-propagating flame, buoyancy is destabilizing. The calculations determine OH concentrations from solution of the two-dimensional fluid dynamic equations with equations of conservation of mass, energy, and species and with chemical rate equations.

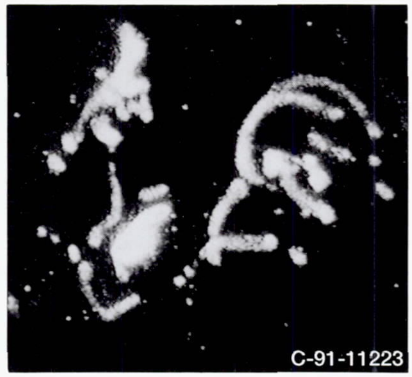



Figure 22.—Propagation of flames in a reduced-gravity environment aboard the KC-135. Long, cylinderlike flame structures are formed that subsequently break into flame balls. The gas composition before ignition was 5 percent hydrogen and 95 percent air.

mixtures, fewer and fewer flame balls are produced until, near the apparent flammability limit, only one or two flame balls evolve from the ignition source.

Flame balls are possibly the only gaseous flame structure in which convective transport plays no role and, thus, are unique to gravity-free environments. Though they had never before been observed, classical theory suggested that such structures were possible but that they should be unstable in the absence of heat loss. More recent theory, developed in response to the experimental observations, suggests that sufficiently strong radiant heat losses may lead to a cell split limit and the formation of stable flame balls. An alternative theory suggests that chemical kinetic mechanisms alone can lead to a cell split limit (see fig. 21). In longer tests in the KC-135 aircraft, $g$-jitter creates considerable motion of the flame balls. The motion of the flame balls frequently generates long, cylinder-like elements of flame that subsequently break into flame balls, as shown in figure 22. It is unclear whether this behavior is related to the longer duration of reduced-gravity or to the residual $g$-levels present. Longer reduced-gravity environment tests are necessary to determine the stability of these flames.

Another unusual phenomenon is observed in microgravity in rich mixtures of propane, oxygen, and carbon dioxide. As the mixture is progressively diluted with carbon dioxide, the amount and rate of flame propagation decreases until the mixture becomes nonflammable. Upon further dilution, it becomes flammable again. This behavior has been termed dilution-enhanced flammability (DEF). In every other known

mixture, dilution decreases flammability. Eventually, sufficient dilution causes permanent nonflammability. In the DEF region only flame balls and discontinuous cellular structures are observed. The DEF behavior probably cannot be attributed to the existence of the negative temperature coefficient regime of reaction rates. Recent theory suggest that the DEF behavior may be attributable to the effect of dilution on the nondimensional heat loss, that is, on the ratio of radiative heat loss to heat generation rate experienced by the flame balls.

In the studies described above, radiative properties of the flames often control its behavior. As a means of varying radiative properties independently of other transport and chemical properties, combustible mixtures seeded with small mass fractions of inert, radiant particles are being studied (see fig. 23). For sufficiently small inert-particle loadings, increasing the particle loading should increase the net radiative loss from the system. For weakly burning mixtures, sufficient particle loadings could result in extinction due to radiative losses. It is observed in dilute methane and air mixtures that the flame temperature and flame speed decrease slightly. Higher, optically thick particle loadings produce a higher burning rate than without the particles. Theory predicts that the burning rates should increase; nonflammable mixtures could become flammable and radiative preheating of the mixture would result in superadiabatic temperatures at the flame front.

The premixed gas experiments described above involve flames freely propagating inside closed vessels. Other experiments, with porous plate burners, have allowed the investigation of stationary flames. Premixed propane-oxygen-nitrogen flames were observed at normal gravity and microgravity to study the role of buoyancy in the overall stability of cellular flames. For most mixtures throughout the cellular regime, gravity has little effect on the structure of premixed burner-stabilized flames. Most of the differences in flame structure can be explained by changes in the flow field external to the premixed flames, as well as by the change in flame speed with $g$ level. The presence of heat losses to the burner overwhelm the effects of removing buoyancy. However, flames propagating in a tube placed vertically on the burner, so as to eliminate the effects of heat loss to the burner, exhibit dramatic changes in behavior in reduced gravity. The downward-propagating flames that in normal gravity are planar (i.e., noncellular) become, in reduced gravity, curved toward the unburned mixture, forming a single cell and nearly filling the tube. This behavior is consistent with theoretical predictions that flat flames are possible only when the stabilizing effect of buoyancy balances the effect of the hydrodynamic instability mechanism. The downward-propagating flames that are cellular in normal gravity produce flames with large, irregular cells in reduced gravity. The cells in these reduced-gravity flames often disappear as a single cell grows into an oblique curved flame, as shown in figure 24. From these results, it was concluded that buoyancy contributes to the overall flame stability and structure but it is not the dominant mechanism in cell formation.

Current experimental efforts involving burner-stabilized flames are investigating weakly turbulent, premixed gas flames. These studies will characterize the behavior of the aerodynamic flow field and mean flame properties for a variety of fuels, flow rates, and turbulence levels to assist in understanding the relationships between gravity level and the onset and structure of turbulent combustion.

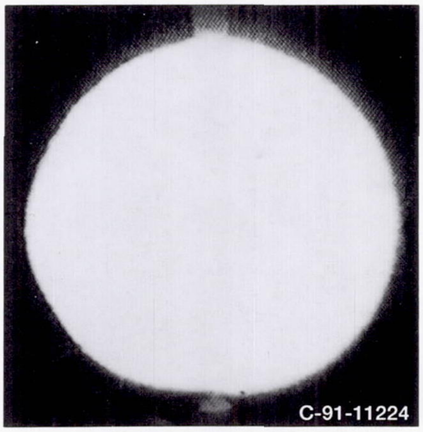



Figure 23.—Radially outward propagation of premixed gas flames seeded with inert, radiant particles to investigate radiative properties of the flame. The premixed gas mixture of 5.2 percent methane and 94.8 percent air was seeded with 0.6-μm silicon carbide particles (12 percent mass loading) before central ignition. Experiment was conducted in the NASA Lewis 2.2-Second Drop Tower.

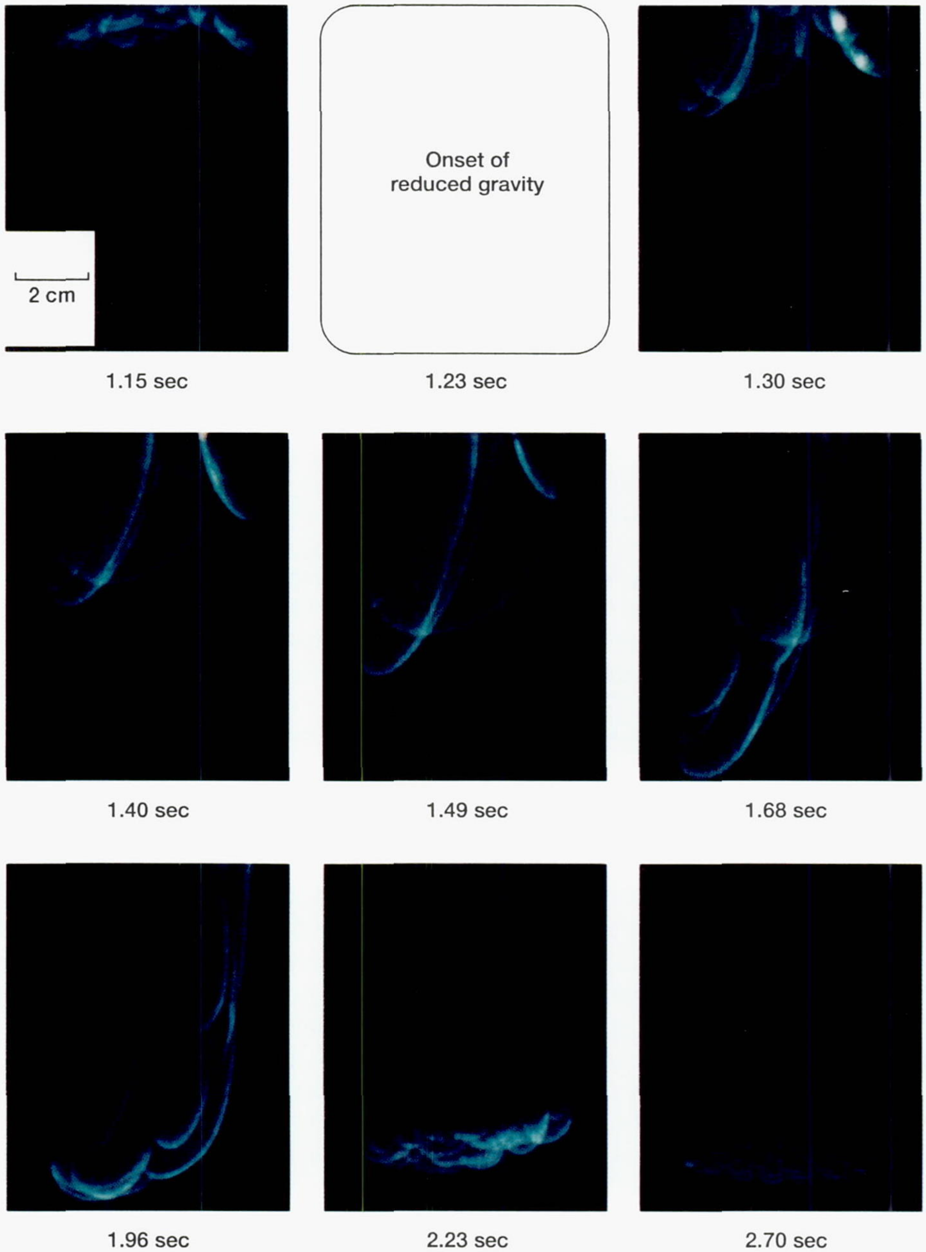


Figure 24.—Drop tower test of a downward-propagating cellular flame in a tube. The flame becomes chaotic in reduced gravity. Heat loss effects become evident when the flame approaches a cold burner at 2.23 sec. Ignition is in normal gravity.

## Gas-Jet Diffusion Flames

Gas-jet diffusion flames embody mechanisms operating in both unwanted fires and controlled combustion systems. The flame structure is controlled by the complex interaction of many mechanisms (fig. 25). Because of its geometric simplicity, the gas-jet diffusion flame is often studied as a first step toward understanding the complex diffusion-flame processes, especially the soot formation and radiative transfer that are found in practical combustion systems. By studying gas-jet diffusion flames in a reduced-gravity environment, where the

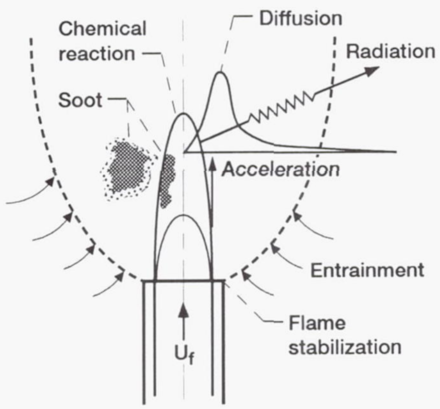



Figure 25.—Schematic of the structure of a laminar gas jet diffusion flame; a complex function of the depicted mechanisms.

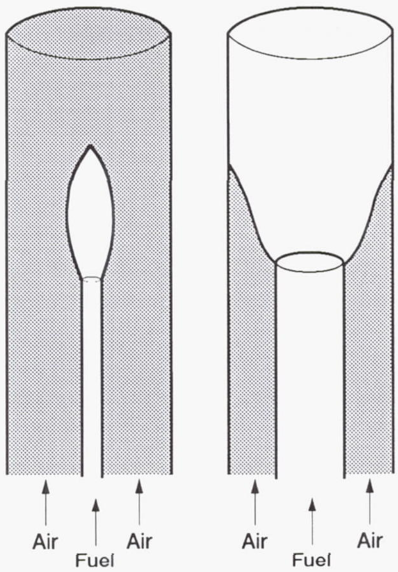



Figure 26.—Burke-Schumann diffusion flame – cylindrical geometry.

effects of buoyancy on flow entrainment and acceleration are reduced, the analyses of heat and mass transfer and soot processes are simplified. A second benefit of studying flames in reduced gravity is the acquisition of data that may aid in improving spacecraft fire safety.

A further simplification can be made by studying flames in the laminar-flow regime. These flames share many qualities with the more complex, but more common, turbulent flames. The following studies have been instituted to understand both laminar and turbulent gas-jet diffusion flames.

**Burke-Schumann diffusion flames.**—The classical example of a gas-jet diffusion flame is that studied by Burke and Schumann in 1928. In their configuration, the flame is enclosed, and a coaxial flow of oxidizer (i.e., air) surrounds the fuel jet. Depending on the inlet conditions, the flame can be either overventilated or underventilated (fig. 26). Burke and Schumann derived an analytical model of the flame to predict its size and shape. The model can reasonably predict the flame height; however, the predicted flame shapes do not precisely match those observed in the normal-gravity experiments. For example, in normal gravity, the observed shape of the tip of an overventilated flame is somewhat pointed and conical, while the predicted tip shape is rounded and elliptical.

It was suggested that the microgravity flame shapes would more closely match the predicted shapes, because the model assumes that buoyant forces are negligible. Studies of laminar Burke-Schumann diffusion flames were conducted in the 2.2-Second Drop Tower to test this suggestion. Both fuel type (methane, ethane, and propane) and inert diluent type (nitrogen, helium, or argon) and concentration in oxygen were varied. The microgravity flames were about the same height as the normal-gravity flames (within 30 percent), as shown in figure 27. The weak effect of buoyancy on the flame height is apparently due to a balance between two opposing effects on the flame. The buoyant force accelerates the flow, causing an increase in flame height (assuming a constant fuel residence time). However, the buoyant

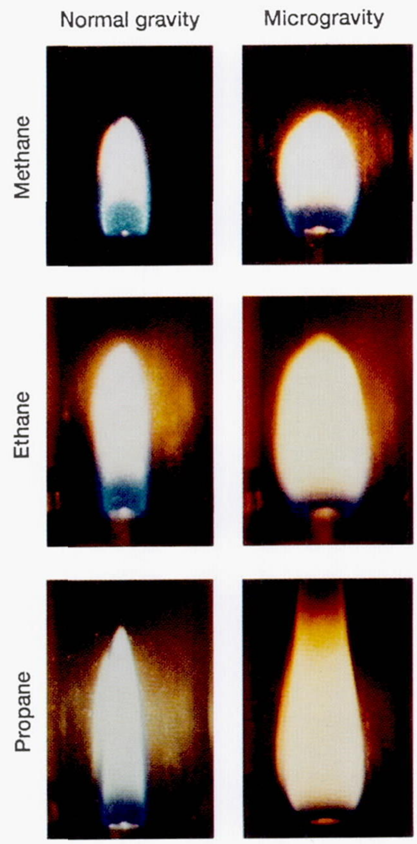



Figure 27.—Cylindrical Burke-Schumann diffusion flame shape images for different fuels and gravity levels. Oxidizer, air; *inlet velocity ratio*, $U_{fu}/U_{ox}$, 1.37; inner tube radius, 0.28 cm; outer tube radius, 2.33 cm; oxygen consumption, ~2.5 $cm^3$/sec.

entrainment increases the rate of oxygen transport to the flame, causing a decrease in flame height (assuming a constant velocity). The microgravity flames were significantly wider than the normal-gravity flames and matched the shapes predicted by the Burke-Schumann analysis better. Thus, the microgravity flame shape was well predicted by the Burke-Schumann model. The principal exception was the flame-tip opening that was observed in some of the microgravity flames (see the propane flame in fig. 27). The flame tip opening was not observed in normal gravity or in any of the methane flames. The opening, unpredicted by the model, was apparently a local extinction due to a combination of reduced oxygen transport to the flame and of radiative heat loss (probably related to greater soot production in microgravity) from the flame.

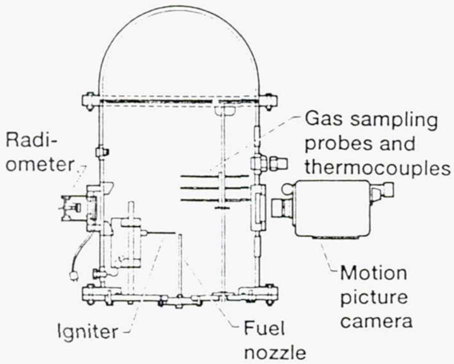


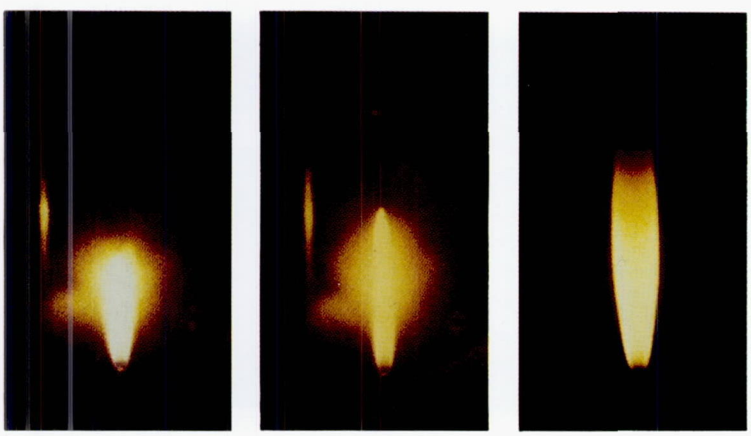

Figure 28.—Hardware for the laminar gas-jet diffusion-flame studies in the Zero-Gravity Facility and the KC-135 research aircraft.

**Laminar gas-jet diffusion flames.**—Microgravity experiments in the Zero-Gravity Facility have also been conducted where the flame is within a quiescent oxidizing environment, as illustrated in figure 28. In an effort to reveal the steady-state flame structure, the combined effects of the fuel type, fuel flow rate, chamber pressure, and oxygen concentration are being studied. Measurements have been restricted to cinematography, thermocouples, and radiometers. As shown in figure 29, the observed microgravity flames are longer, wider, and often sootier than their normal-gravity counterparts. They are dimmer and more reddish, which indicates a lower flame temperature. Some microgravity flames appear to have open tips, as found in the Burke-Schumann flames. The microgravity flames exhibit no flickering, even though their normal-gravity counterparts clearly flicker. This supports the hypothesis that the flicker is due to a hydrodynamic instability of the buoyancy-induced flow field.

Examination of the temperature and radiation data has shown that some propane flames do not reach steady-state conditions in the 5-sec drop tests. Further testing is now being planned with longer times at lower gravitational levels in the KC-135 aircraft and the Shuttle.

Because the microgravity flames are generally larger and sootier, the thermal radiation from the flame and its surroundings can be an order of magnitude greater in microgravity than normal gravity. However, at low oxygen concentrations, blue, soot-free flames appear in microgravity, whereas the identical normal-gravity flames do not show any significant reduction in soot formation at low oxygen concentrations. This lack of correspondence between normal and microgravity soot formation may make it more difficult to calibrate traditional particle sensing fire detectors for use in reduced gravity.

More detailed investigations concentrating on soot processes and radiative characteristics of laminar gas-jet diffusion flames are underway. Soot production is an important pathway for a significant fraction of the fuel in many flames, and, consequently, to understand the chemistry and transport in these flames, the soot processes must be understood. Because of its radiative properties, soot is a major con-



Normal gravity, minimum flame height | Normal gravity, maximum flame height | Microgravity

**Figure 29.—Effect of gravity on a propane flame burning in quiescent air. The propane jet exits the nozzle (internal diameter, 0.165 cm) at 1.5 $cm^3$/sec into the experiment chamber at 1.0 atm. Variations in height at normal gravity are due to flame flicker caused by buoyancy.**

tributor to the radiative heat loss from a flame. As a result, it plays a major role in energy extraction from flames in large scale boilers and is very important in spacecraft and terrestrial fire safety. Soot is composed of a range of aromatic hydrocarbon species that are important combustion products both from toxicity and fire detection standpoints.

Traditionally, similarities between gas-phase processes in laminar and turbulent diffusion flames have been exploited to gain a better understanding of turbulent diffusion flames. Unfortunately, laminar diffusion flame studies in normal gravity do not have corresponding utility as model flame systems for soot processes because of the differential diffusion between soot particles and gases in the buoyantly accelerated flow, limited spatial resolution and residence times, and intrinsic unsteadiness. Since, in microgravity, laminar-jet diffusion flames do not experience these difficulties, an ongoing study is specifically investigating soot processes. Ground-based laboratory experiments consist of the development of short-duration ($\simeq$0.5 sec) drop tests that will be instrumented with stationary-laser extinction soot measurement, flow visualization, and flow measurement systems that will acquire data as the drop package falls through the measurement volume. Results for steady and unsteady (pulsed) flames will be compared in order to highlight the effects of vorticity that are characteristic of turbulent flames. A companion, Shuttle-based experiment will study similar flames with somewhat reduced diagnostic capability but considerably longer burning times. As currently envisioned, the experiments will measure the temperature and soot fields of ethylene and propane laminar jet diffusion flames.

Theory suggests that diffusion flames in microgravity may extinguish due to radiative heat loss from particulates (e.g., soot) that drain chemically released energy from the flame. This mechanism of extinction may be unique to microgravity. In normal gravity the hot particulates formed in the fuel-rich flames are swept upward by buoyancy, out of the flame to the region above it, where their influence on the flame is negligible. In microgravity, the particulates may remain in the flame vicinity, creating a strong energy sink that can, under suitable conditions, cause flame extinction. A microgravity investigation will use a porous spherical burner to permit simple comparison with theory. The effects of buoyancy may be simulated by imposing a forced crossflow on the otherwise purely radial flow field produced by the efflux from the porous sphere.

**Turbulent gas-jet diffusion flames.**—Buoyancy is often cited as the cause of the onset of turbulence in gaseous diffusion flames. It is reasonable to question whether the conditions leading to the onset of turbulence in normal gravity will yield a turbulent flame in microgravity. An investigation has also been initiated to study the effects of buoyancy on gas-jet diffusion flames in the laminar-to-turbulent transition regime (see fig. 30). Flames in this regime are characteristic of unconfined fires. Tests will be conducted in ground- and space-based facilities to determine the relative importance of buoyancy-induced turbulence on flame characteristics. The initial tests are now starting in the 2.2-Second Drop Tower.

As with laminar flames, the sooting characteristics and radiative transport in turbulent gas-jet diffusion flames is the focus of a new study. The radiative heat transfer from sooting, turbulent diffusion flames may represent the majority of the theoretical heat release by

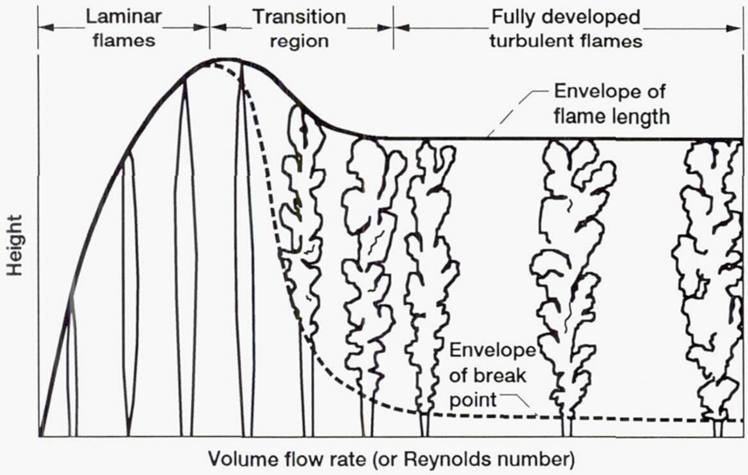


Figure 30.—Change in flame height and behavior with increase in volume flow rate (or Reynolds number) for a typical gas-jet diffusion flame. (Adapted from Hottel, H.C., and Hawthorne, W.R., *Third Symposium on Combustion*, Williams and Wilkins, p. 254, 1949.)

combustion. Modeling of these flames and their corresponding flow fields will be based on a Favre-averaged $k$-$\varepsilon$-$g$ turbulence model and the laminar flamelet approximation, with modifications to include soot formation and radiative heat transfer. In addition to soot, measurements of the flame-zone temperature and velocity distributions will be made, since they are both affected by the sooting characteristics. Both nonintrusive optical measurements and thermophoretically captured soot sampling will be used. Several of the advanced diagnostic techniques described in a later section of this document will be first tried in the 2.2-Second Drop Tower study.

## Droplet Combustion

The study of droplet and spray combustion is important from purely scientific, practical, and fire-safety perspectives. From a purely scientific perspective, single-droplet burning represents the simplest example of nonpremixed combustion that involves the participation of a liquid phase. From a practical one, liquid fuels burned in the form of sprays are a major source of energy now and for the foreseeable future. Reduced-gravity facilities offer a unique environment to study some of the important features of droplet and spray combustion without the added complication of buoyant convection.

In practical sprays, because of the small droplet diameters ($\simeq 100\ \mu$m), buoyant forces are typically small. The time scales associated with burning these small droplets are also small, which, coupled with the small size, makes studying them in a normal-gravity environment difficult. Larger droplet sizes ($\simeq 1$ mm), with correspondingly larger associated time scales, are easier to study, but at the cost of significant buoyant forces. Reduced-gravity facilities allow researchers to investigate the combustion phenomena in a simplified geometrical configuration (spherical symmetry) that is amenable to both theoretical and numerical modeling. The larger length and time scales offered by droplet combustion in reduced gravity means that both liquid and gas-phase transient and quasi-steady phenomena and flame-extinction phenomena can be studied in detail.

Currently, two droplet combustion apparatuses are used in the 2.2-Second Drop Tower and the Zero-Gravity Facility. Both create a near-motionless droplet in a quiescent environment. As shown in figure 31, a droplet is grown by injecting liquid between two horizontally opposed needles. The liquid is stretched by slowly moving the needles apart to reduce the interfacial surface between the liquid and the needles. The droplet is deployed by rapidly and simultaneously retracting the needles and, then, shortly after deployment, is ignited by two horizontally opposed sparks. The droplet is photographed by two cameras: a backlit view to see the droplet and a view orthogonal to the backlit view to see the flame. The ambient pressure and gas composition can be controlled in both apparatuses. Figure 32 shows a droplet combustion experiment from the 2.2-Second Drop Tower of a 2-mm $n$-decane droplet burning in air.

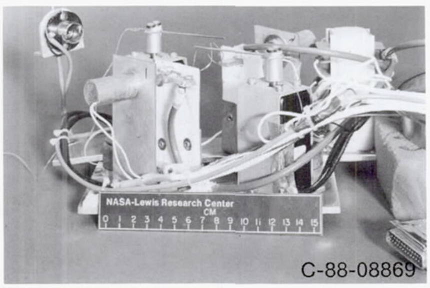


Figure 31.—Droplet combustion experiment apparatus for the Lewis 2.2-Second Drop Tower. The droplet velocity as well as the flame and droplet size are obtained by high speed photography.

Several new phenomena related to droplet combustion have been found during testing in the NASA Lewis drop towers. These phenomena include (1) a new slow-burning regime for droplets; (2) the influence of soot formation on the burning characteristics in hydrocarbon droplet combustion; (3) disruptive burning of initially pure liquid fuel droplets; (4) a lower LOI for droplet combustion in microgravity than normal gravity; (5) the importance of the interaction of the spark and the droplet in the ignition of the droplet; and (6) the identification of product dissolution in the liquid phase of the droplet.

The droplet combustion experiment (DCE), currently approved for spaceflight development, will study the spherically symmetric combustion of a large, pure, fuel droplet (heptane, decane, or methanol) in a quiescent environment. The goals of the DCE are to examine liquid- and gas-phase steady and unsteady phenomena and flame-extinction phenomena in single-droplet combustion. By varying the pressure and oxygen concentration, the location of the flame relative to the droplet can be varied to place the flame in either a convective-diffusive region (high oxidizer concentration) or a transient-diffusive region (low oxidizer concentration). The liquid-phase phenomena consist mainly of transient liquid heating and product dissolution and transport into the liquid phase. The study of flame extinction is of particular interest, because reduced gravity allows large extinction droplet sizes to be studied. These large extinction droplet sizes correspond to large characteristic chemical kinetic times not attainable in ground-based laboratories.

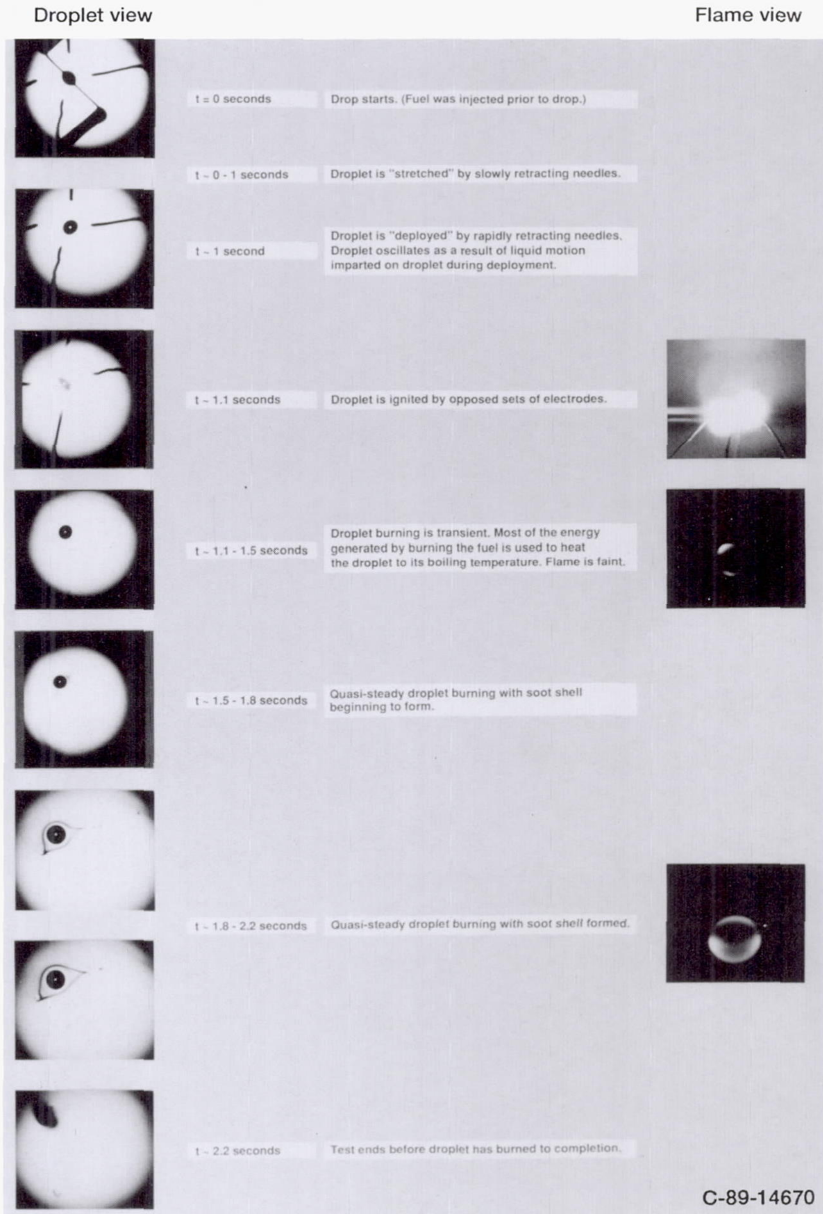



Figure 32.—Images of a 2-mm decane droplet burning in air under reduced-gravity conditions.

**Multicomponent droplets.**—Although the combustion of pure liquid droplets is interesting and important, practical fuels are rarely pure. The first approximation to a more practical, multicomponent fuel is the study of fuel droplets that consist of two pure fuels, that is, a bicomponent fuel droplet. Again, reduced gravity provides an ideal environment for the study of bicomponent droplet combustion by enabling larger length and time scales to be examined.

Two particular phenomena of interest in bicomponent droplet combustion are the droplet burning history and the possibility of disruptive burning. The burning history of the bicomponent droplet

may exhibit three-stage burning because of its dependence on the liquid-phase mass transport. During the initial stages of burning, if liquid-phase mass transport is diffusion limited, then the more volatile component will vaporize and burn preferentially. This results in a liquid-phase boundary layer in the droplet, because liquid mass diffusion is typically slower than droplet surface regression. With the more volatile component depleted, the droplet begins heating to the boiling temperature of the less volatile component. This heating stage is followed by the third, quasi-steady stage of burning. The phenomena of disruptive burning, or microexplosion, occurs when, during combustion, a pocket of more volatile fuel is heated above its homogeneous nucleation temperature. For bicomponent droplet combustion, disruptive burning can result if a higher concentration of the more volatile fuel is trapped at the core of a droplet surrounded by a shell of a less volatile fuel and if there is a sufficient volatility difference between the two fuels.

NASA currently supports three reduced-gravity, bicomponent droplet combustion investigations. The first, which is focussed mainly on the combustion of smaller droplets ($\approx 500\ \mu m$) at atmospheric pressures (for heptane/hexadecane mixtures), has produced neither three-stage burning nor disruptive burning behavior. The second, which uses fiber-supported, 0.7- to 1-mm droplets at pressures up to 12 atm, has shown three-stage burning but no disruptive burning in a low oxygen environment. The third investigation, which is both theoretical and experimental, is in its initial stages. It consists of theoretically predicting the three-stage burning behavior and refining the developed model based on comparisons with experimental data obtained using one of the droplet combustion apparatus described above.

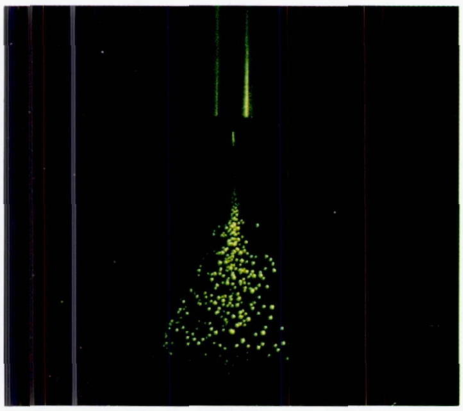


Figure 33.—Electrospray under single-laser pulse illumination.

**Droplet arrays and fuel sprays.**—In practical fuel sprays, droplets do not burn individually but interact with each other during combustion. It is insufficient, then, to base models of fuel-spray combustion entirely on results from single-droplet combustion experiments. Two studies currently underway will extend the results of single-droplet combustion studies to more practical fuel sprays.

The goal of the first study is to extend single-droplet studies to simple one- and two-dimensional arrays of a small number of droplets in a controlled situation that more closely simulates an actual fuel spray, but is still amenable to detailed analytical treatments. The experiment consists of using fiber-supported droplets where the relative droplet geometry can be easily controlled. The fiber apparatus will be housed in a sealed chamber so that the environment can be controlled. The experiment will be conducted primarily in the drop towers and aircraft.

The second study recently underway examines the combustion of electrostatically generated monodisperse sprays (see fig. 33) in reduced gravity. The electrostatic spray generation method allows self-dispersion of the spray due to Coulombic repulsion and control of droplet trajectories. These characteristics of the electrospray allow fuel-spray combustion to be studied in simplified experimental configurations starting with laminar gas flows and gradually moving to more complex fully turbulent gas flows.

## Particle Cloud Combustion

The study of combustible particle clouds is of fundamental scientific interest as well as a practical concern. Such clouds serve to spread fires in underground mining operations and contribute to the fire and explosion hazards of grain storage and handling facilities. Analogous to premixed gas combustion, of principal scientific interest are the characteristic combustion properties, especially flame structure, propagation rates, stability limits, and the effects of stoichiometry, transport phenomena, and nonadiabatic processes on these properties.

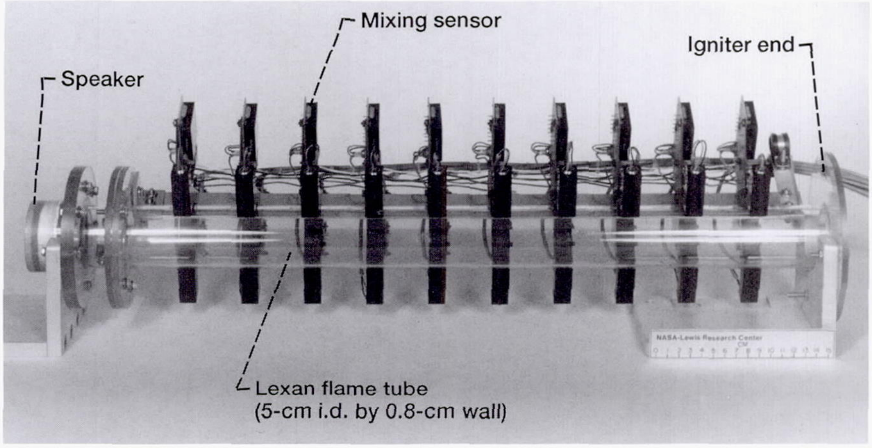



Figure 34.—Flame tube assembly for particle cloud combustion experiment. The tests were performed on the Lewis Learjet in the following stages: (1) lycopodium fuel particles (30-μm spheres) were mixed into cloud form by 0.5-sec sound burst from the loud speaker: (2) particle motion was allowed to decay toward quiescence during a 7-10 sec waiting period: (3) an igniter was energized, which both opened one end of the tube and ignited the particle cloud: and (4) the flame proceeded down the tube length, with its position and shape recorded by high-speed cameras. Ten optical sensors determined cloud uniformity and flame position.

The experimental study of quiescent, uniform particle clouds has not been accomplished in normal gravity because of particle settling. In attempts to achieve uniformity, stirring devices or particle feeders have been used, but in such schemes, quiescence is sacrificed and a time-dependent turbulent field in introduced that affects flame propagation and limits behavior. Furthermore, buoyantly driven flows induced by the spreading flame interact with the turbulent field in a manner beyond the current state of understanding.

As an alternative, a reduced-gravity experiment was performed that emulates the characteristics of classical premixed gas studies and minimizes particle settling and buoyantly driven flows. Figure 34 describes the experiment in which a flame propagates through a cloud of lycopodium (a type of organic spore) particles suspended inside a standard 5-cm-diameter flammability tube. A cloud uniformity on the order of ±15 percent of the mean concentration was achieved. For fuel-rich mixtures, quasi-steady flame propagation was observed. The observed shape of the flame front and wake structures were as anticipated but not previously obtained (see fig. 35(a)). A new model based on asymptotic analysis has been developed for these flames; it suggests that the leading edge of the flame propagates through a fuel-lean gas-phase mixture even when the fuel-air ratio based on the solid-particle concentration is fuel-rich. Continuous vaporization and burnoff of the particles occurs in the tail of the flame.

For near-unity solid-fuel to air ratios, “chattering flame” propagation was observed (see fig. 35(b)). These flames did not propagate steadily through the tube but, instead, induced an acoustic disturbance. There remains some uncertainty about the flame-acoustic phenomenology. Original speculation suggested that the acoustic disturbance segregated the air-suspended, unburnt particles into alternating fuel-rich and fuel-lean laminae. The flame then propagated in a leaping, or chattering, fashion from one fuel-rich regime to the next, principally by radiative preheating and autoignition. Subsequent tests with improved photography, temperature, and pressure measurements revealed that laminae are formed only in the hot combustion

products. It has been suggested that chattering flames are not observed for fuel-rich mixtures, partially because the fuel particles damp the acoustic signal.

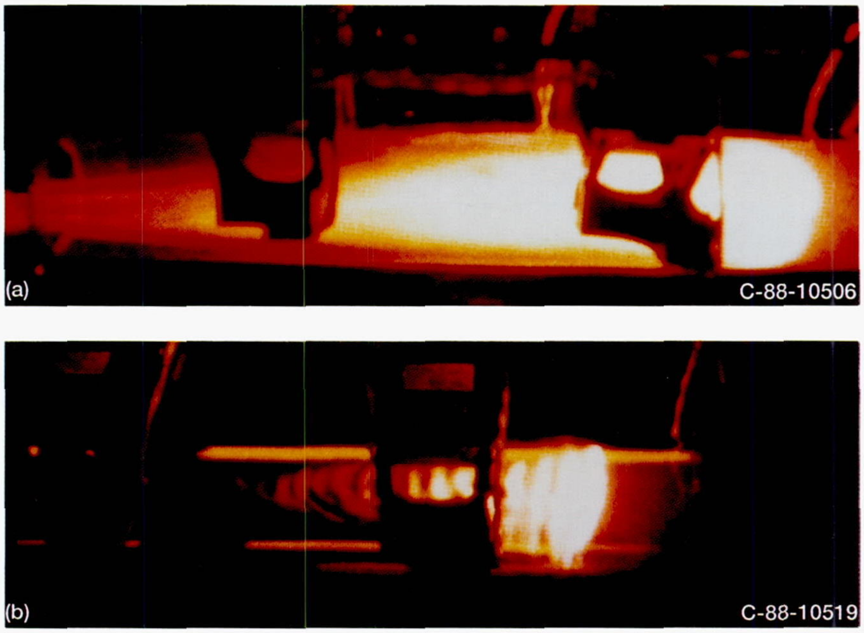



Figure 35.—Fuel-rich and near-stoichiometric flames photographed during particle cloud combustion experiment. (a) The long, continuous, symmetric tail is characteristic of lycopodium fuel-rich flames (here, with an equivalence ratio of 2.2). Had this experiment been performed in normal gravity, the flame front and tail would have been bent upwards due to buoyancy. The observed flame speed (not the fundamental burning velocity) was about 40 cm/sec. (b) The luminous tail of the near-stoichiometric, chattering flame is discontinuous and shorter than the flame in part (a). Chattering flames propagate more slowly and less steadily through the tube, on the order of 20 cm/sec.

## SPACECRAFT FIRE SAFETY

Information applicable to fire safety for practical reduced-gravity environments (i.e., for orbiting spacecraft) is an important byproduct of the aforementioned fundamental combustion research. A more complete understanding of combustion phenomena and flame characteristics contributes to the improvement of material acceptance standards, fire detection, extinguishment, and postfire rehabilitation in space. Moreover, reduced-gravity combustion research is necessary in assessing the effects of certain hazards that may be unique to or may be aggravated in space—smoldering or aerosol fires, for example.

Currently, NASA and international human-crew space missions emphasize fire prevention through selection of acceptable materials, storage control of necessary flammable exceptions, and adherence to standards of ignition prevention. The overall fire-protection strategy includes smoke detection for early warning and fixed and portable fire extinguishers for suppression, using techniques adopted from aircraft practices. The experience with the few incidents on the Shuttle has shown that the present fire protection is adequate. Nevertheless, there is now a growing attention to research and technology to investigate and improve present spacecraft fire-safety practices. There are several reasons for the increased scientific and engineering interest.

(1) Safety strategies are evolutionary processes and must be subject to periodic review and updating as the knowledge of microgravity combustion grows and new consensus standards in aircraft and related fields are developed.

(2) The complex and long-duration missions and environment of future spacecraft, particularly the permanently orbiting Space Station *Freedom*, create a demand for innovative approaches to fire safety.

(3) Improved knowledge can optimize safety factors and provide tradeoffs of minimal risk against greater utilization of spacecraft facilities.

Thus, the continuing application of recognized state-of-the-art fire-safety designs for spacecraft is being supplemented by the results, as yet limited in scope, of studies of combustion processes in microgravity. For example, the previous studies of the ignition and burning of paper are especially relevant because paper is a flammable material that must be accepted for use in space. Furthermore, paper ignition can occur at a lower energy flux than for many common polymeric materials because they form an insulating surface-char layer.

Three research projects in the field of fire science related to practical fire safety can be cited. The first is a critical study of flammability-assessment methods for spacecraft materials. NASA has already tested over 7000 nonmetallic materials in order to assess their acceptability for use in air and enriched-oxygen environments. For materials in sheet form, a standard test determines the resistance to upward flame spread upon promoted ignition in normal gravity. The critical study addresses two concerns about the utility of the NASA flammability test. First, the test is a pass-fail assessment; thus it does not measure quantitative flammability through ignition delay, flame spread rate, or heat release, all of which are important parameters for predictive and comparative analyses. Second, the test, of necessity, is conducted in normal gravity, and a safety factor for the flammability behavior in microgravity must be assumed. It is not the purpose of the critical study to propose a new procedure for NASA testing, since the development of standard methods is beyond the scope of the research. The results to date suggest, however, that the NASA test may be made more representative of incipient fire situations in space by incorporating other testing techniques, including sample preheating and multiple-surface self-heating.

The second microgravity spacecraft fire-safety project aims to adapt the methods of probabilistic risk assessment (PRA) to spacecraft. The PRA techniques define probabilities of fire initiation and propagation scenarios and calculate fire-detection, fire-growth, and fire-suppression times to establish quantitative risks. Inherent in the development of the risk assessments is the acquisition of fundamental data on ignition, burning efficiency, mass burning rates, combustion products, smoke production, and adjacent surface damage. Thus, small-scale, microgravity experiments are essential to provide these data for the risk analyses. Eventually, the project should lead to the development of an in-space experiment that is the preferred means of acquiring the full-scale, long-duration information necessary for the detailed PRA.

The third spacecraft fire-safety project is a study of bulk metal ignition and combustion in microgravity. Oxygen storage and handling systems are common and important components in spacecraft. Preliminary studies have indicated that, in some cases, common metals are made more flammable under oxygen in reduced gravity because the

molten flame zone adheres to the solid-metal fuel instead of separating and dripping under the influence of gravity.

Despite the promise of the studies in progress, it is evident that important issues are yet to be addressed in spacecraft fire safety. The subjects that offer opportunities for research in combustion and related fields of study are noted in the following list.

(1) Determination of correlations of microgravity to normal-gravity flammability for practical quantitative material acceptance criteria for spacecraft materials

(2) Evaluation of early-warning detection techniques for overheating, smoldering, and flaming fires based on studies of the detectible characteristics of these phenomena

(3) Development of centralized and multiple-sensor systems for efficient and optimized fire detection

(4) Determination of the efficiency, response, and physical dispersion of conventional and innovative extinguishers in microgravity fires

(6) Evaluation of methods for continuous monitoring of atmospheric contaminants in spacecraft for fire warning and environmental control

(7) Investigation of hazards from flammable aerosols in space (spills, etc.)

(8) Calculation of numerical field fire-scenario models for the prediction of ventilation patterns, optimum detection, and fixed suppression locations and escape routes

(9) Introduction of artificial intelligence (expert systems) and automation to guide fire detection, extinguishment, and evacuation responses

(10) Development of techniques for postfire cleanup of combustion and extinguishment products from the spacecraft atmosphere and surfaces.

## MICROGRAVITY COMBUSTION DIAGNOSTICS DEVELOPMENT

The achievement of a significant scientific return from existing and proposed microgravity combustion science experiments depends substantially on the availability of diagnostic systems. To date, instrumentation has been limited, consisting primarily of conventional film-based imaging systems and intrusive temperature and velocity probes such as thermocouples and hot-wire anemometers. This situation has arisen primarily because of the severe operational constraints of microgravity experimentation. The need for more sophisticated diagnostic systems has motivated this development effort.

Most emphasis has been on the development of optical diagnostic techniques for a variety of reasons. Principal among these is the nonperturbative nature of optical instruments, which makes them well suited to the acquisition of multidimensional data sets from reduced-gravity environments where buoyantly driven, vigorous (and, hence, less easily disturbed) flows are absent.

As with all microgravity experiments, development proceeds from the normal-gravity laboratory to the ground-based facilities to spaceflight hardware. At present, none of the advanced techniques described in the following sections has made it to the last stage; however, plans

are to include them in the multiuser hardware described later in this document.

## Qualitative Imaging of Flames and Flow Fields

Qualitative visualization has long been acknowledged as an important element in the understanding of combustion phenomena. It is an essential aid in the interpretation of single-point temperature, species-concentration, and velocity measurements and in the assessment of the time and length scales of processes occurring in the flow field. In microgravity combustion science, the need for low-light-level visualization is particularly strong, since most systems of interest operate near the limits of flammability, ignition, or stability and are subsequently too weakly luminescent to be visualized by conventional means.

Two approaches will be described in this section: band-filtered imaging using intensified array cameras and reactive seeding methods. Infrared imaging and schlieren photography are also applicable for this purpose and are described in the next two sections.

Solid-state, charge coupled device (CCD) cameras with microchannel plate intensifiers are being used to image flame structures that are below the sensitivity range of conventional detectors or photographic films. The intensifier, in essence, amplifies the incoming photons, thereby increasing the detector's luminous sensitivity by as much as four orders of magnitude. This increased sensitivity permits the use of narrow bandwidth spectral filters, which may be used to isolate specific emissions or to mask the effect of more luminous regions, such as blackbody radiation from soot.

Previous investigations of the combustion of premixed hydrogen gas mixtures required the addition of chemicals, such as fire-retarding Halons, in order to make the flames visible. But researchers suspected that the coloring agents might have some effect on flame behavior. The use of the intensified array camera in reduced-gravity premixed combustion tests aboard the NASA KC-135 revealed heretofore unseen flame structures and behavior, especially in dilute hydrogen mixtures (see figs. 20 and 22). Future work involves extending capabilities to include photocathodes with sensitivity in the ultraviolet range.

Attempts in the laboratory to use lower pressures and higher oxygen concentrations to emulate the reduced-gravity combustion of solids have been partially successful, in that they have provided valuable information about the ability of filters to block soot radiation and isolate emission bands. As shown in figure 36, reduced-gravity tests aboard the Lewis Learjet recently used the solid-surface combustion experiment chamber with an intensified array camera to image weakly luminous flames spreading over paper samples.

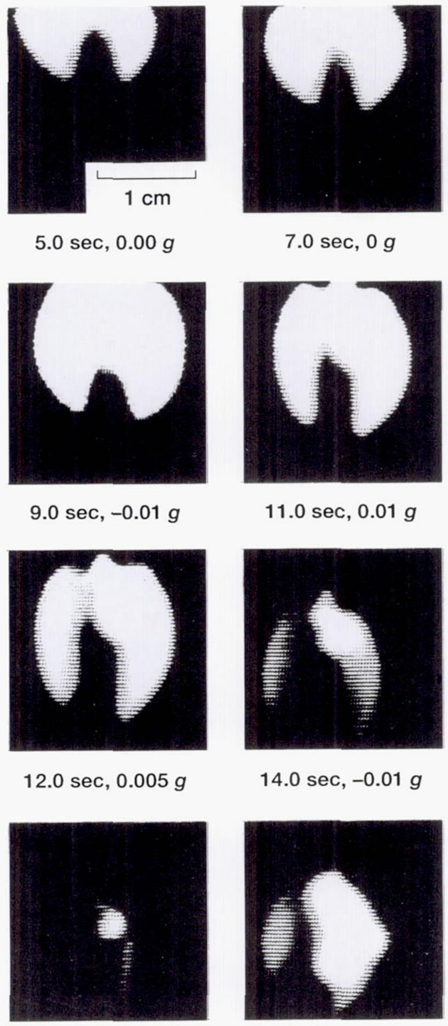



Figure 36.—Flame spread over ashless filter paper in air. An intensified array camera views the flame as it propagates over the sample during a reduced-gravity experiment aboard the Lewis Learjet.

## Infrared Imaging

Platinum silicide (PtSi) imaging arrays have recently become available for the near- and mid-infrared wavelength bands. The arrays permit the visualization of weak flames even while using narrow bandwidth filters. This opens the possibilities for performing two-dimensional temperature field measurements of known emissivity

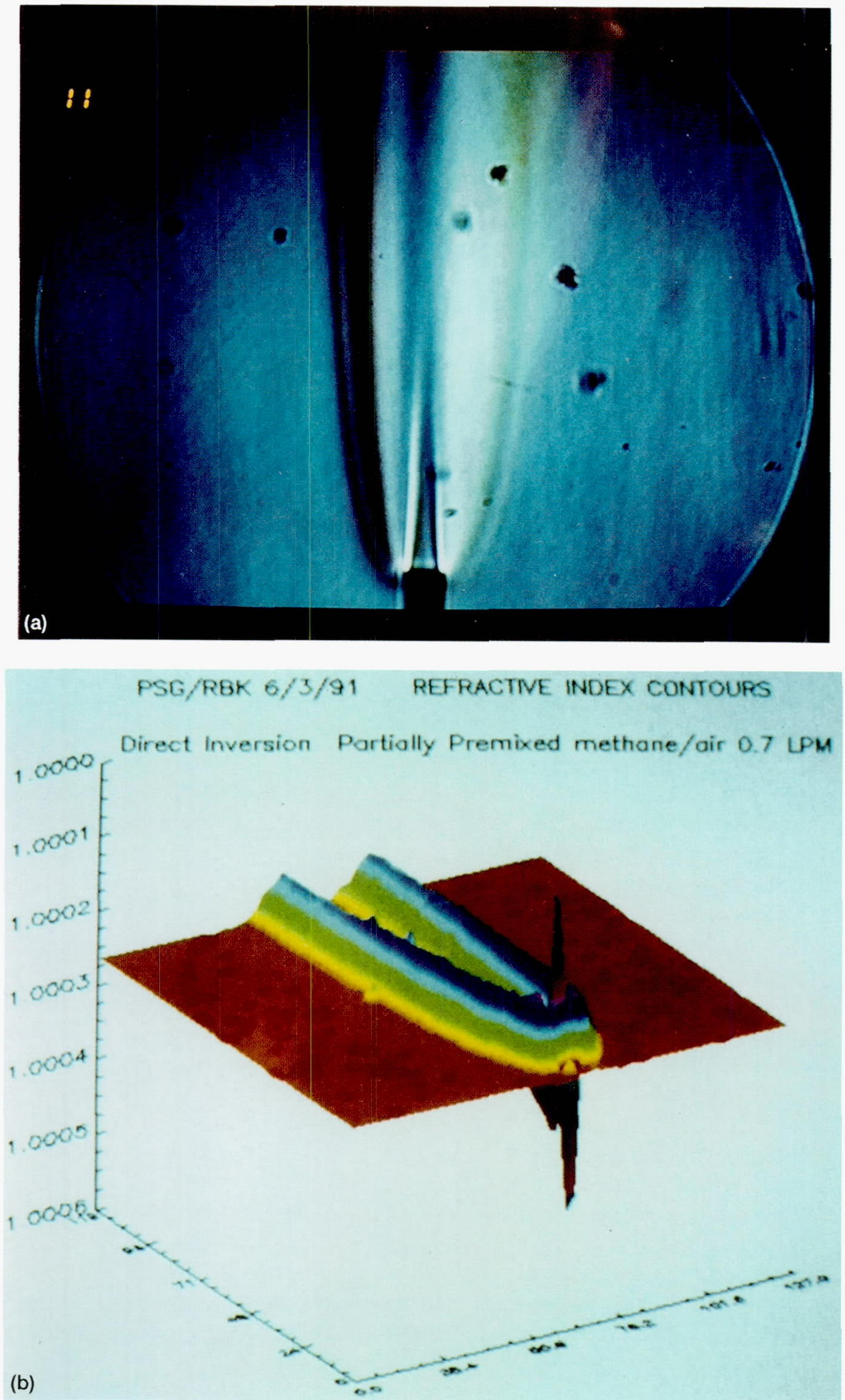



Figure 37.—Rainbow schlieren application to stoichiometric methane and air gas-jet diffusion flames. (a) Raw color image and (b) tomographic reconstruction of the resulting refractive index field.

radiators, such as soot or grids of thin (15 μm), ceramic fibers. Ceramic fiber grids are already being successfully used in the drop towers for the qualitative assessment of temperature distributions in gas-jet diffusion flames. Extension to quantitative radiative thermometry appears to be reasonably straightforward.

A more complete characterization of combustion in the infrared spectrum may enable, in certain cases, the determination of major species concentrations and temperatures. For simple fuels, resolving the spectrum through a suitable series of band-pass filters could be sufficient; more complicated systems may require a more elaborate approach, such as an imaging spectrometer or Fourier transform infrared spectroscopy (FTIR). The first step in this effort has been the acquisition of computer code that predicts the IR emission spectra for a specified combustion process. Initially, simple premixed and diffusion flames will be investigated. The predicted spectra will be verified experimentally using a conventional scanning monochromator. The objective is to invert the process: the measured emission spectra become the input for the calculation of the species concentrations and local temperatures.

An IR imaging array camera has recently been delivered. Band-pass filters suitable for viewing emissions from water, carbon dioxide, and carbon monoxide are available. Acquisition of images and spectra for comparison to calculated spectra for gaseous flames are planned.

## Rainbow Schlieren

The determination of refractive index fields has long been used to qualitatively visualize combustion reactions by their ability to indicate temperature distributions or relative species concentrations in nonreacting flows. For these purposes, interferometric methods of determining refractive indexes are not ideally suited, principally because of their strict requirements for mechanical stability. Deflectometric methods, such as schlieren and moire, are far less complex, more tolerant to mechanical and thermal fluctuations, and readily adaptable to large fields of view.

The system presently under development is based on the use of continuously graded color rainbow filters. The qualitative appearance of the observed images (see fig. 37(a)) affords great detail, owing to the human eye's ability to resolve fairly subtle differences in color. The continuous nature of the color filter offers better spatial resolution than conventional knife-edge methods. Furthermore, a simple image digitization and processing system has been demonstrated to quantify the color attributes of the observed image and, hence, the ray deflection that produced it. Sensitivity comparable to conventional interferometry has been achieved. This system has been used in the laboratory to measure refractive index distributions in radiantly heated liquid pools and in axially symmetric jet diffusion flames (fig. 37). A system of this type is being assembled for reduced-gravity tests in the 2.2-Second Drop Tower.

## Soot Transmission, Scattering, and Thermophoretic Sampling

The chemistry of the formation of soot and the substantial heat loss due to radiation motivate an increased understanding of the role of soot in microgravity combustion phenomena. Specifically, the mass fraction and size distribution are desirable quantities to determine

experimentally. Experiments are being conducted in the laboratory and in a new 2.2-Second Drop Tower rig (fig. 38) that uses transmission, scattering, and sampling techniques. Transmission measurements are accompanied by either the collection of soot samples or by an additional scattering measurement. The initial configuration of the drop-tower rig accommodates full-field absorption measurements using a low-power laser source and soot sampling using a thermophoretic probe. For the probe, small-wire electron microscopy grids are rapidly inserted into the flame and withdrawn (total residence time of approximately 30 msec). High-speed schlieren imaging is used to validate the essentially nonintrusive nature of the probe. The size distribution of the soot particles may then be analyzed from scanning electron micrographs and used to compute an effective soot absorption cross section and soot number densities. Data obtained under normal-gravity conditions agree well with published values.


Figure 38.—2.2-Second Drop Tower package for optical diagnostics development supporting soot characterization measurements and particle image velocimetry studies.

## Particle Image Velocimetry

Particle image velocimetry represents a broad class of techniques for the instantaneous measurement of velocities over a plane of interest within a flow field. Typically, the flow field is seeded with small particles. Scattering from an incident sheet of laser light is then imaged onto an array detector or photographic medium. The particle trajectories, obtained by recording a sequence of exposures, can be used to calculate the local velocity vectors.

In the Young's fringe reduction-processing method, a multiply exposed photograph of the type described above is reduced by sequen-

tially interrogating successive regions of the image with a thin, pencil-like beam of coherent light. The image is degraded by photographic grain in the background that resembles the phenomena of laser speckle. In addition, decorrelating mechanisms within the flow field, such as turbulence, need to be accounted for. The present effort involves the development and optimization of a noise model to clarify the influence of various experimental parameters (e.g., the seeding density, size of the interrogation beam, and local properties of the field itself) on the overall measurement accuracy.

A new experimental technique for data reduction has also been developed. The vector scanning, or VS method, differs somewhat from most current approaches in that the digitized particle image field is searched directly rather than transformed or correlated. The VS method operates far more efficiently than computationally intensive transforms; an entire particle image field can be processed in a matter of seconds on a standard PC. One of the diagnostics drop packages being constructed for the 2.2-Second Drop Tower contains instruments for recording multiply exposed particle image data.

## Laser Doppler Velocimetry

Laser Doppler velocimetry (LDV) is a nonintrusive optical technique for the accurate determination of pointwise velocity data. In some instances, it is possible to perform line or area scans before the flow field has evolved significantly. Recent developments in solid-state laser diode and avalanche photodiode detector technologies have made available LDV systems that are quite compact and require only a few watts of electrical power. Initial testing is planned in the laboratory and on aircraft.

# MULTIUSER SPACEFLIGHT HARDWARE

Multiuser hardware is a logical means for achieving efficient use of space-based facilities for microgravity combustion research. Use of common subsystems in hardware development avoids the high cost of repeatedly developing flight-qualified hardware. Multiuser hardware is also expected to be more flexible in adapting to new science and design requirements thereby extending its useful life. However, the specification of design parameters for flight hardware that must be compatible with experiments several years from conception is not practical. Hence, NASA has adopted an evolutionary approach to multiuser spaceflight hardware that will provide the opportunity to simultaneously nurture the science of microgravity combustion and the technology of space-based experiments. Experiment payloads that are dedicated to the requirements of a single investigator, such as the solid-surface combustion experiment, will be followed by more advanced Shuttle and Space Station Freedom payloads that can accommodate a wide class of experiments.

For the Shuttle-based experiments we will attempt to use a common set of components and subsystems in required configurations for a first series of flight experiments. These experiments will use the middeck lockers and Getaway Special canisters (GASCAN's). Sounding

rockets and cargo-bay-mounted systems will also be analyzed for potential use by these experiments. The first multiuser facility, where many of these components and subsystems will be permanently mounted, will be the combustion module (CM–1). Versions of CM–1 are being designed for installation on Spacelab and Space Station Freedom.

## Shuttle Combustion Experiments

Currently, three payloads are planned:

(1) (Middeck) solid-fuels combustion hardware, which will be used initially to study flaming of solid fuels such as polymethylmethacrylate (PMMA)

(2) (Middeck) droplet combustion hardware, which will be used for the study of transient combustion of nearly motionless liquid-fuel droplets

(3) (GASCAN) smoldering combustion hardware, which will be used to study the smoldering characteristics of polyurethane foam.

This next generation of space-based combustion experiments will involve liquid fuels for the first time. In each case, the volume of the combustion chamber on the middeck will remain comparable to SSCE. Instrumentation planned for these payloads include standard and intensified film and video imagers, thermocouples, pressure transducers, gas sampling probes, and radiometers. Experiments may be conducted in quiescent or flowing-gas environments. Flow provisions will be made by means of a closed, recirculating system (duct) incorporating a fan and flow straighteners.

Initial Space Shuttle flights for these payloads are planned for early 1995 with additional flights often thereafter.

## Combustion Module 1

The prospect of a permanently inhabited, orbiting laboratory is about to be realized with Space Station *Freedom*. Researcher astronauts will work in a laboratory specifically designed for microgravity experiments. To fully use this capability, the combustion module (CM–1) is being planned to accommodate multiple combustion experiments. The CM–1, now in the conceptual stage, will be the first true, multiuser, space-based, combustion facility. As shown in figure 39, it is conceived as a highly modular system with instrumentation hardware commonly needed by many experiments and a combustion chamber and optical assembly for experiment-specific apparatus. The flexibility to perform diverse experiments will be achieved by use of reconfigurable apparatus and diagnostic instrumentation. The CM–1 is planned to accommodate a wide spectrum of combustion experiments, including laminar gas-diffusion flames, premixed gas flames, and fires with small amounts of liquid and solid fuels.

The CM–1 will incorporate combustion chambers of twice the interior volume of SSCE. Both quiescent and flowing environments would be provided. As with the Shuttle payloads described above, flow could be provided by a closed, recirculating system or, if adequate gas storage is available, by an open-loop blowdown system. Multiple

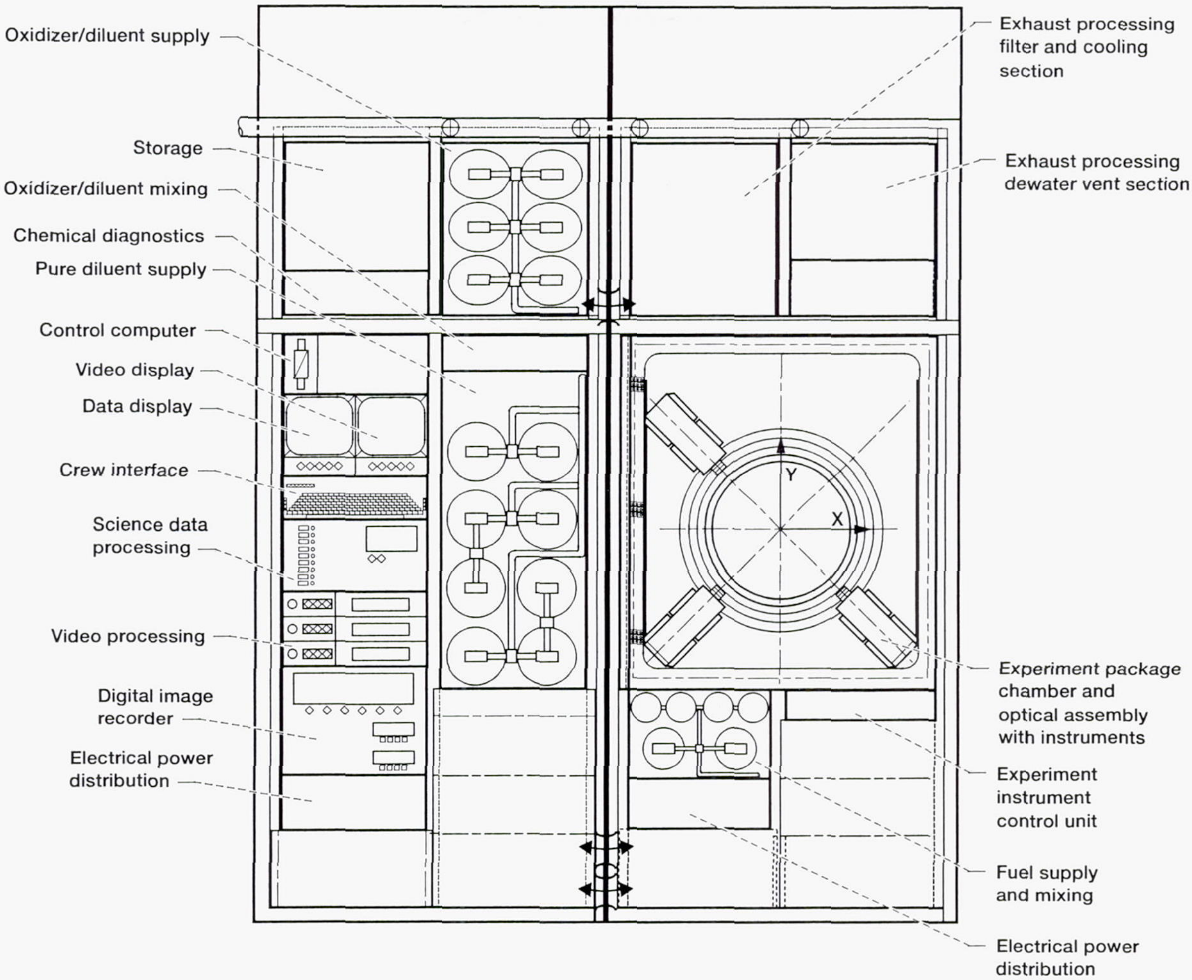



Figure 39.—Planned combustion experiments module (CM-1) for Spacelab consists of two double racks. Instrumentation hardware commonly needed by many experiments is installed in one double rack; the second double rack contains the combustion chamber/optical assembly.

experiments, with or without combustion-chamber atmosphere changeout, will be possible.

Nonintrusive diagnostics techniques will be a major component of CM–1. It is expected that velocity-field mapping capabilities will include particle image velocimetry, density-gradients imaging by means of color and/or schlieren techniques, and particulate (e.g., soot) loading by means of light absorption and extinction techniques. Imaging of combustion will be not only in the visible wavelengths, but also in the infrared and ultraviolet. In addition, standard instrumentation such as thermocouples, pressure transducers, and gas-sampling probes will be provided.

The eventual long duration of a space station mission (90 days as compared with 14 days for an extended Spacelab mission) will allow extensive apparatus and diagnostic changeout or reconfiguration so that a highly productive combustion laboratory will be available to serve the needs of a diverse scientific community. In addition, high-fidelity communications between the investigators on Earth and the astronaut-scientist could make possible the nearly real-time investigation of unanticipated findings.

# OPPORTUNITIES FOR PROGRAM PARTICIPATION

NASA provides financial and facility support, typically for a three-year "definition study" period, to academic and industrial principal investigators. Their initial proposals and subsequent progress are evaluated via a peer review process that addresses the following types of questions:

(1) Is there a clear need for microgravity experimentation, particularly space-based experimentation?

(2) Is the effort likely to result in a significant advance to the state of understanding?

(3) Is the scientific problem being examined of sufficient (i.e., widespread) intrinsic interest or practical application?

(4) Is the conceptual design and technology required to conduct the experiment sufficiently developed to ensure a high probability of success?

Principal investigators may work alone or collaborate with a NASA technical monitor to conduct the necessary research. Work in the drop towers and aircraft is strongly encouraged in this period. If, after the definition study, spaceflight experiments are deemed justified, the principal investigators may propose through a competitive solicitation (described below) a Shuttle flight experiment. If the proposal wins support through this solicitation, it becomes a flight candidate. Soon thereafter, the principal investigators present their detailed objectives, test requirements, and the conceptual hardware design to another independent review panel composed of scientific and engineering peers who assess the ability of the proposed flight experiment to meet its objectives. If the proposal passes this review, NASA assigns a team of engineers and scientists to the multiyear development of spaceflight hardware that meets the principal investigator's specifications. NASA continues to support the principal investigators throughout this development to conduct further research, provide consultation, and support the design and safety reviews prior to spaceflight. The nominal time frame from flight experiment candidacy to manifest on the Shuttle is five years. The principal investigators then monitor the conduct of the experiment in flight and subsequently analyze and are obliged to publish the data in an archival journal.

The above scenario is typical for Shuttle-based experiments; however, NASA also supports theoretical and diagnostics research as well as microgravity experiments that can be conducted in drop towers or aircraft. Proposals for either definition study or flight experiment candidacy are solicited via a NASA Research Announcement (NRA). The first NRA focussed on microgravity combustion science was issued in December 1989. It resulted in 13 definition study awards and 6 flight experiment candidacy awards out of 65 proposals. An NRA for microgravity combustion science will be issued every three years. During the period between combustion-specific NRA's, generic, multidiscipline NRA's will be issued annually. The proposals that result from these NRA's will be subject to peer review; proposers should allow roughly 6 to 9 months for an assessment and notification of acceptance or rejection. Finally, NASA offers graduate students financial support through its Graduate Student Research Program, and postdoctorate fellowships through the National Research Council. More information

about these programs and the process of proposal submission, progress reviews, and spaceflight project selection is available by writing to the Microgravity Combustion Branch, MS 500–217, NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135.

# APPENDIX — CURRENT MICROGRAVITY COMBUSTION SCIENCE AND SPACECRAFT FIRE SAFETY PROJECTS

(Note: * indicates that the investigation is a candidate flight experiment)

"Low-Velocity, Opposed-flow Flame Spread in a Transport-Controlled, Microgravity Experiment"*
Robert A. Altenkirch
Mississippi State University
P.O. Drawer DE
College of Engineering
Mississippi State, MS 39762

Co-Investigators: S. Bhattacharjee and S.L. Olson

"Solid Surface Combustion Experiment"*
Robert A. Altenkirch
Mississippi State University
P. O. Drawer DE
College of Engineering
Mississippi State, MS 39762

"Risk-Based Fire Safety Experiment"
George E. Apostolakis and Ivan Catton
University of California, Los Angeles
Mechanical, Aeronautical, and Nuclear Engineering Department
Los Angeles, CA 90024–1597

"An Experimental and Theoretical Study of Radiative Extinction of Diffusion Flames"
Arvind Atreya and Indrek S. Wichman
Michigan State University
Department of Mechanical Engineering
East Lansing, MI 48824

"The Combustion of Free or Unsupported Fuel Droplets at Low Gravity"
Thomas Avedisian
Cornell University
Ithaca, NY

"Gravitational Effects on Turbulent Gas-Jet Diffusion Flames" *
Yousef Bahadori
Science Applications International Corp.
21151 Western Avenue
Torrance, CA 90501–1724

Co-Investigators: R. Edelman and D. Stocker

"Ignition and Combustion of Bulk Metals in a Microgravity Environment"
Melvin C. Branch and John W. Daily
University of Colorado
Department of Chemical Engineering
Boulder, CO 80309–0427

"Modeling of Microgravity Combustion Experiments"

John Buckmaster
University of Illinois at Urbana-Champaign
Aeronautical and Astronautical Engineering Department
Urbana, IL 61801

"Gravitational Effects on Premixed Turbulent Flames: Studies of Dynamics of Wrinkled Laminar Flames in Microgravity"

Robert K. Cheng
Lawrence Berkeley Laboratory
Combustion Group, Applied Science Division
B29C-102
Berkeley, CA 94720

"Combustion of Interacting Droplet Arrays in a Microgravity Environment"

Daniel L. Dietrich
Sverdrup Technology, Inc., LeRC Group
MS 500–217
21000 Brookpark Road
Cleveland, OH 44135–3191

Co-Investigator: J. Haggard

"Investigation of Laminar Jet Diffusion Flames in Microgravity: A Paradigm for Soot Processes in Turbulent Flames"*

Gerard M. Faeth
The University of Michigan
Department of Aerospace Engineering
Ann Arbor, MI 48109–2140

"A Fundamental Study of Smoldering Combustion in Microgravity"*

A. Carlos Fernandez-Pello
University of California at Berkeley
Department of Mechanical Engineering
Berkeley, CA 94720

Co-Investigator: P. Pagni

"Subcritical and Supercritical Vaporization and Burning of Mono and Multi-component Single Droplets"*

Iskender Gokalp
Centre National de La Recerche Scientifique
45071 Orleans Cedex 2, France

"Combustion of Electrostatic Sprays of Liquid Fuels in Laminar and Turbulent Regimes"

Alessandro Gomez
Yale University
Department of Mechanical Engineering
New Haven, CT 06520

Co-Investigators: M. Smooke and M. Long

"Ignition and Subsequent Flame Spread in Microgravity"

Takashi Kashiwagi
National Institute of Standards and Technology
Building and Fire Research Laboratory
Gaithersburg, MD 20899

"Modeling of Premixed Gas Flames in Microgravity"

K. Kailasanath
Naval Research Laboratory
Laboratory for Computational Physics
Washington, DC

Co-Investigators: E. Oran and G. Patnaik

"Measurements and Modeling of Sooting Turbulent Jet Diffusion Flames Under Normal and Reduced Gravity Conditions"

Jerry C. Ku
Wayne State University
Mechanical Engineering Department
Detroit, MI 48202

Co-Investigator: P. Greenberg

"Studies of Flame Structure in Microgravity"

C.K. Law
Princeton University
Department of Mechanical and Aerospace Engineering
Engineering Quadrangle
Princeton, NJ 08544

"Measurement of the Quenching Distance for Dust-Air Mixtures in a Microgravity Environment"*

John H.S. Lee and R. Knystautus
McGill University
Department of Mechanical Engineering
Montreal, PQ, Canada

"Spacecraft Material Flammability Testing with Radiative Self-Heating"

Thomas J. Ohlemiller
National Institute of Standards and Technology
Building and Fire Research Laboratory
Gaithersburg, MD 20899

"Low Speed Convective Flow Effects on Flame Spread over Thin Fuels"

Sandra L. Olson
NASA Lewis Research Center
MS 500-217
21000 Brookpark Road
Cleveland, OH 44135–3191

"Laminar Premixed Gas Combustion Experiments in Space"*

Paul D. Ronney
Princeton University
Department of Mechanical and Aerospace Engineering
D323, Engineering Quadrangle
Princeton, New Jersey 08544

"Ignition and Flame Spread Across Liquid Pools" *

Howard D. Ross
NASA Lewis Research Center
MS 500-217
21000 Brookpark Road
Cleveland, OH 44135–3191

Co-Investigator: W. Sirignano

"The Structure of Particle Cloud Premixed Flames"

K. Seshadri and A. Berlad
University of California at San Diego
Center for Energy and Combustion Research, R-011
La Jolla, CA 92093–0411

"Combustion Experiments in Reduced Gravity with Two-Component Miscible Droplets"

Ben Shaw
University of California at Davis
Department of Mechanical Engineering
Davis, CA 95616

"Combustion of Solid Fuel in Very Low Speed Oxygen Streams"

James S. T'ien
Case Western Reserve University
Department of Mechanical and Aerospace Engineering
Cleveland, OH 44106

Co-Investigator: K. Sacksteder

"High-Pressure Combustion of Binary-Fuel Droplets"

Forman A. Williams
University of California at San Diego
Center for Energy and Combustion Research, R-011
La Jolla, CA 92093-0411

Co-Investigators: J. Sato and T. Niioka

"Scientific Support for a Space Shuttle Droplet Burning Experiment"*

Forman A. Williams
University of California at San Diego
Center for Energy and Combustion Research, R-011
La Jolla, CA 92093-0411

and

Frederick L. Dryer
Princeton University
Engineering Quadrangle
Princeton, NJ 08544

# SELECTED BIBLIOGRAPHY

## Review Papers

Altenkirch, R.A.; Bhattacharjee, S.; Olson, S.L.; and West, J.: Opposed Flow Flame Spread in Normal, Enhanced, and Reduced Gravity. Proc. 1st AIAA/IKI Microgravity Science Symposium, AIAA, 1991, pp. 305–313.

Berlad, A.L.: Particle Cloud Combustion in Reduced Gravity. Ch. 7 in Low-Gravity Fluid Dynamics and Transport Phenomena, J.N. Koster and R.L. Sani, eds., AIAA, 1990.

Choi, M.Y., Cho, S.Y., Dryer, F.L., and Haggard, J.B., Jr.: Some Further Observations on Droplet Combustion Characteristics: NASA LeRC–Princeton Results. IKI/AIAA Meeting, Moscow, USSR, May 1991.

Faeth, G.M.: Homogeneous Premixed and Nonpremixed Flames in Microgravity: A Review. IKI/AIAA Meeting, Moscow, USSR, May 1991.

Law, C.K.: Combustion in Microgravity: Opportunities, Challenges, and Progress. Presented at the 28th Aerospace Sciences Meeting, Jan. 1990, AIAA Paper 90–0120.

Sacksteder, K.: The Implications of Experimentally Controlled Accelerations for Combustion Science. 23rd Symposium (International) on Combustion, Combustion Institute, Pittsburgh, PA, 1990, pp. 1589–1596.

Williams, F.A.: Combustion Phenomena in Relationship to Microgravity Research. Micrograv. Sci. Technol., vol. 3, Dec. 1990, pp. 154–161.

## Research Papers

Abbud-Madrid, A.; and Ronney, P.D.: Effects of Radiative and Diffusive Transport Processes on Premixed Flames near Flammability Limits. 23rd Symposium (International) on Combustion, Combustion Institute, Pittsburgh, PA, 1990, pp. 423–431.

Apostolakis, G.E.: Fire Risk Assessment for Manned Spacecraft. Presented at PSA '89, the International Topical Meeting on Probabilistic Reliability and Safety Assessment, Pittsburgh PA, Apr. 2–7, 1989.

Apostolakis, G.E.; Ho, V.S.; Marcus, E.; Perry, A.T.; and Thompson,A.T.: Risk-Based Fire Safety Experiment Definition for Manned Spacecraft. NASA CR–183855 (also UCLA Report ENG 90–11; NAS8–37750), 1989.

Bahadori, M.Y.; Edelman, R.B.; Sotos, R.G.; and Stocker, D.P.: Radiation from Gas-Jet Diffusion Flames in Microgravity Environments. AIAA Paper 91–0719, 1991.

Bahadori, M.Y.; Edelman, R.B.; Stocker, D.P.; and Olson, S.L.: Ignition and Behavior of Laminar Gas-Jet Diffusion Flames. AIAA J., vol. 28, Feb. 1990, pp. 236–244.

Bahadori, M.Y.; Stocker, D.P.; and Edelman, R.B.: Effects of Pressure on Microgravity Hydrocarbon Diffusion Flames. AIAA Paper 90–0651, 1990.

Berlad, A.L.; Ross, H.D.; Facca, L.; and Tangirala, V.: Particle Cloud Flames in Acoustic Fields. Combust. Flame, vol. 82, Dec. 1990, pp. 448–450.

Berlad, A.L.; and Tangirala, V.: Autoignition of Fuel-Oxidizer Mixtures in Microgravity, IAF Paper 87–385, 1987.

Berlad, A.L.; Tangirala, V.; Ross, H.D.; and Facca, L.: Radiative Structure of Lycopodium-Air Flames in Low Gravity. AIAA Paper 89-0500, 1989.

Bhattacharjee, S.; and Altenkirch, R.A.: Radiation-Controlled, Opposed-Flow Flame Spread in a Microgravity Environment. 23rd Symposium (International) on Combustion, Combustion Institute, Pittsburgh, PA, 1990, pp 1627–1633.

Bhattacharjee, S.; Altenkirch, R.A.; Olson, S.L.; and Sotos, R.G.: Heat Transfer to a Thin Solid Combustible in Flame Spreading at Microgravity. J. Heat Trans., vol. 113, Aug. 1991, pp. 670–676.

Bhattacharjee, S.; Altenkirch, R.A.; Srikantiah, N.; and Vedha Nayagam, M.: A Theoretical Description of Flame Spreading over Solid Combustibles in a Quiescent Environment at Zero Gravity. Combust. Sci. Technol., vol. 69, no. 1–3, 1990, pp. 1–15.

Buckmaster, J.; Clavin, P.; and Matalon, M.: Particle Cloud Combustion and Chattering Flames. Presented at the International Symposium on Pulsating Combustion, Monterey, CA, Aug. 1991.

Buckmaster, J.D.; Joulin, G.; and Ronney, P.D.: Effects of Heat Loss on the Structure and Stability of Flame Balls. Combust. Flame, vol. 79, no. 3–4, 1990, pp. 381–392.

Buckmaster, J.D.; Joulin, G.; and Ronney, P.D.: The Structure and Stability of Nonadiabatic Flame Balls: II. Effects of Far-Field Losses. Combust. Flame, vol. 84, Apr. 1991, pp. 411–422.

Cantwell, E.R.; and Fernandez-Pello, A.C.: Smoldering Combustion under Low Gravity Conditions; Drop Tower. AIAA Paper 90–0648, 1990.

Cho, S.Y.; Choi, M.Y.; and Dryer, F.L.: Extinction of a Free Methanol Droplet in Microgravity. 23rd Symposium (International) on Combustion, Combustion Institute, Pittsburgh, PA, 1990.

Cho, S.Y.; Yetter, R.A.; and Dryer, F.L.: Computer Model for Chemically Reactive Flow with Complex Chemistry/Multi-component Molecular Diffusion/Heterogeneous Processes. J. Comput. Physics, to appear.

Cho, S.Y.; Yetter, R.A.; and Dryer, F.L.: Mathematical Modelling of Liquid Droplet Combustion in Microgravity. Presented at the Seventh International Conference on Mathematical and Computer Modelling, 1992.

Choi, M.Y.; Dryer, F.L.; and Haggard, J.B., Jr.: Observations of a Slow Burning Regime for Hydrocarbon Droplets: *n*-Heptane/Air Results. 23rd Symposium (International) on Combustion, Combustion Institute, Pittsburgh, PA, 1990.

Choi, M.Y.; Dryer, F.L.; Haggard, J.B., Jr.; and Brace, M.H.: Some Further Observations on Microgravity Droplet Combustion in the NASA Lewis Drop Tower Facilities: A Digital Processing Technique for Droplet Burning Data. Drops and Bubbles: Third International Colloquium, T.G. Wang, ed., American Institute of Physics, New York, 1989, pp. 338–361.

Cochran, T.H., ed.: Combustion Experiments in a Zero-Gravity Laboratory. Progress in Aeronautics and Astronautics, Vol. 73, AIAA, Washington, DC, 1981.

Dunsky, C.M.; and Fernandez-Pello, A.C.: Gravitational Effects on Cellular Flame Structure. 23rd Symposium (International) on Combustion, Combustion Institute, Pittsburgh, PA, pp. 399–412, 1990.

Edelman, R.B.; and Bahadori, M.Y.: Effects of Buoyancy on Gas Jet Diffusion Flames: Experiment and Theory. Acta Astronaut., vol. 13, no. 11/12, 1986, pp. 681–688.

Edelman, R.B.; Fortune, O.F.; Weilerstein G.; Cochran, T.H.; and Haggard, J.B., An Analytical and Experimental Investigation of Gravity Effects upon Laminar Gas Jet Diffusion Flames. 14th Symposium (International) on Combustion, Combustion Institute, Pittsburgh, PA,1973.

Edelman, R.B.; Fortune, O.; and Weilerstein, G.: Analytical Study of Gravity Effects on Laminar Diffusion Flames. NASA CR–120921, 1973.

Farmer, J.N.; and Ronney, P.D.: A Numerical Study of Unsteady Nonadiabatic Flames. Combust. Sci. Technol., vol. 73, no. 4–6, 1990, pp. 555–574.

Ferkul, P.V.: An Experimental Study of Opposed Flow Diffusion Flame Extinction Over a Thin Fuel in Microgravity. NASA CR–182185, 1989.

Friedman, R.; and Dietrich, D.L.: Fire Suppression in Human-Crew Spacecraft. J. Appl. Fire Sci., vol. 1, 1991, pp. 243–258. (Also available as NASA TM–104334.)

Friedman, R.; and Olson, S.L.: Fire Safety Applications for Spacecraft. AGARD CP2–467, 1989, pp. 15-1–15-15. (Also available as NASA TM–101463.)

Friedman, R.; Sacksteder, K.R.; and Urban, D.L.: Risks, Designs, and Research for Fire Safety in Spacecraft. NASA TM–105317, 1991.

Haggard, J.B., Jr.; Brace, M.H.; Dryer, F.L.; Choi, M.Y.; Williams, F.A.; and Card, J.: *n*-Decane-Air Droplet Combustion Experiments in the NASA Lewis 5 Second Zero-Gravity Facility. AIAA Paper 90–0649, 1990.

Haggard, J.B., Jr.; and Kropp, J.L.: Development of a Droplet Combustion Experiment for Low Gravity Operations. AIAA Paper 87–0576, 1987.

Haggard, J.B., Jr.; Williams, F.A.; Card, J.; Dryer, F.L.; Choi, M.Y.; and Cho, S.Y.: *n*-Decane Droplet Combustion in the NASA Lewis 5-Second Zero-Gravity Facility: Results in Test Gas Environments Other Than Normal Air. AIAA Paper 91–0720, 1991.

Hamins, A.; Meitor, M.; and Libby, P.A.: Gravitational Effects on the Structure and Propagation of Premixed Flames. Acta Astronaut., vol. 17, 1988, pp. 503–514.

Hegde, U.; and Bahadori, M.Y.: Gravitational Influences on the Behavior of Confined Diffusion Flames. AIAA Paper 92–0334, 1992.

Hegde, U.; Ross, H.D.; and Facca, L.T.: Longitudinal Mode Instabilities of Particle Cloud Combustors in a Low Gravity Environment. Presented at the International Symposium on Pulsating Combustion, Monterey, California, Aug. 1991.

Kailasanath, K.; and Oran, E.S.: Effect of Curvature and Dilution on Unsteady Flame Propagation: I. Flames and Configurations. Chapt. in Dynamics of Reactive Systems, Flames and Configurations, J.R. Bowen, J.-C. Leyer, and R.I. Soloukhin, eds., (Vol. 105, pt. 1, of Prog. Aero. & Astron.), 1986.

Kailasanath, K.; Patnaik, G.; and Oran, E.: Effect of Gravity on Multi-Dimensional Laminar Premixed Flame Structure. IAF Paper 88–354, 1988.

Knight, B.; and Williams, F.A.: Observations on the Burning of Droplets in the Absence of Buoyancy. Combust. Flame, vol. 38, 1980, pp. 111–119.

Kushida, G.; Baum, H.R.; Kashiwagi, T.; and Di Blasi, C.: Heat and Mass Transport in Thermally Degrading Thin Cellulosic Materials in a Microgravity Environment. J. Heat Trans., 1992 (to appear).

Kushida, G.; Baum, H.R.; Kashiwagi, T.; and Di Blasi, C. Mass Transport from Thermally Degrading Thin Cellulose Materials in a Microgravity Environment *J. Heat Trans.*, 1991 (to appear).

Libby, P.A.: Theoretical Analysis of the Effect of Gravity on Premixed Turbulent Flames. Combust. Sci. Tech., vol. 68, 1989, pp. 15–33.

NASA Office of Safety and Mission Quality: Flammability, Odor, Offgassing, and Compatibility Requirements and Test Procedures for Materials in Environments That Support Combustion. NASA NHB 8060.1C, April 1991.

Newhall, J.L.; Fernandez-Pello, A.C.; and Pagni, P.J.: Experimental Observations of the Effect of Pressure and Buoyancy on Cellulose Co-current Smoldering. J. Fire Mater., in press, 1990.

Ohlemiller, T.J.; and Villa, K.M.: Material Flammability Test Assessment for Space Station Freedom. NASA CR–187115, June 1991.

Olson, S.L.: The Effect of Microgravity on Flame Spread Over a Thin Fuel. NASA TM–100195, 1987.

Olson, S.L.: Mechanisms of Microgravity Flame Spread Over a Thin Solid Fuel: Oxygen and Opposed Flow Effects. Combust. Sci. Technol., vol. 76, no. 4–6, 1991, pp. 233–249.

Olson, S.L.; Ferkul, P.V.; and T'ien, J.S.: Near-Limit Flame Spread Over a Thin Solid Fuel in Microgravity. 22nd Symposium (International) on Combustion, Combustion Institute, Pittsburgh, PA, 1988, pp. 1213–1222.

Patnaik, G.; and Kailasanath, K.: Effect of Gravity on the Stability and Structure of Lean Hydrogen-Air Flames. 23rd Symposium (International) on Combustion, Combustion Institute, Pittsburgh, PA, 1990, pp. 1641–1647.

Patnaik, G.; and Kailasanath, K.: Cellular Structure of Lean Hydrogen Flames in Microgravity. AIAA Paper 90–0041, 1990.

Patnaik, G.; Kailasanath, K.; and Oran, E.: The Effect of Gravity on Flame Instabilities in Premixed Gases. AIAA Paper 89–0502, 1989.

Patnaik, G.; Kailasanath, K.; Oran, E.; and Laskey, K.: Detailed Numerical Simulations of Cellular Flames. 22nd Symposium (International) on Combustion, Combustion Institute, 1988, pp. 1517–1526.

Reuther, J.J.: Definition of Experiments to Investigate Fire Suppressants in Microgravity. NASA CR–185295, 1990.

Ronney, P.D.: Effect of Gravity on Laminar Premixed Gas Combustion II: Ignition and Extinction Phenomena. Combust. Flame, vol. 62, Nov. 1985, pp. 121–133.

Ronney, P.D.: Effect of Chemistry and Transport Properties on Near-Limit Flames at Microgravity. Combust. Sci. Technol., vol. 59, no. 13, 1988, pp. 123–41.

Ronney, P.D.: On the Mechanisms of Flammability Limits and Extinguishment Processes at Microgravity. 22nd Symposium (International) on Combustion, Combustion Institute, 1988, pp. 1615–1623.

Ronney, P.D.: Near-Limit Flame Structures at Low Lewis Number. Combust. Flame, vol. 82, Oct. 1990, pp. 1–14.

Ronney, P.D.; and Sivashinsky, G.I.: A Theoretical Study of the Propagation and Extinction of Nonsteady Spherical Flame Fronts. SIAM J. Appl. Math., vol. 49, Aug. 1989, pp. 1029–1046.

Ronney, P.D.; and Wachman, H.Y.: Effect of Gravity on Laminar Premixed Gas Combustion: I. Flammability Limits and Burning Velocities. Combust. Flame, vol. 62, Nov. 1985, pp. 107–119.

Ross, H.D.; Berlad, A.L.; Facca, L.; and Tangirala, V.: Feasibility of Reduced Gravity Experiments Involving Quiescent, Uniform Particle Cloud Combustion. NASA TM–101371, 1988.

Ross, H.D.; and Sotos, R.G.: An Investigation of Flame Spread Over Shallow Liquid Pools in Microgravity and Nonair Environments. 23rd Symposium (International) on Combustion, Combustion Institute, 1990, pp. 1649–1655.

Ross, H.D.; Sotos, Ray G.; and T'ien, J.S.: Observations of Candle Flames Under Various Atmospheres in Microgravity. Combust. Sci. Technol., vol. 75, no. 1, 1991, pp. 155–160.

Rubinstein, R.; and Greenberg, P.S.: Particle Image Fields and Partial Coherence. Appl. Opt., vol. 29, no. 35, 1990, pp. 5282–5291.

Rubinstein, R.; and Greenberg, P.S.: Young's Fringe Velocimetry in the Presence of Random Particle Motions. Proceedings of the Fourth International Conference on Laser Anemometry and Applications, A. Dybbs and B. Ghorashi, eds., ASME, New York, 1991.

Shaw, B.D.: Studies of Influences of Liquid-Phase Species Diffusion on Spherically Symmetric Combustion of Miscible Binary Droplets. Combust. Flame, vol. 81, 1990, pp. 277–288.

Shaw, B.D.; Dryer, F.L.; Williams, F.A.; and Gat, N.: Interactions between Gaseous Electrical Discharges and Single Liquid Droplets. Combust. Flame, vol. 74, Dec. 1988, pp. 233–254.

Shaw, B.D.; Dryer, F.L.; Williams, F.A.; and Haggard, J.B., Jr.: Sooting and Disruption in Spherically Symmetrical Combustion of Decane Droplets in Air. Acta Astronaut., vol. 17, no. 11–12, 1988, pp. 1195–1202.

Shaw, B.D.; and Williams, F.A.: Theory of Influence of a Low-Volatility, Soluble Impurity on Spherically-Symmetric Combustion of Fuel Droplets. Int. J. Heat Mass Transfer, vol. 33, Feb. 1990, pp. 301–317.

Smith, R.L.; and Kashiwagi, T.: Expert Systems Applied to Spacecraft Fire Safety. NASA CR–182266, 1989.

Strehlow, R.A.; Noe, K.A.; and Wherley, B.L.: The Effect of Gravity on Premixed Flame Propagation and Extinction in a Vertical Standard Flammability Tube. 21st Symposium (International) on Combustion, Combustion Institute, Pittsburgh, PA, 1986, pp. 1899–1908.

Weiland, K.J.: Intensified Array Camera Imaging of Solid Surface Combustion aboard the NASA Learjet. AIAA Paper 92–0240, 1992.

Wernet, M.P.; Edwards, R.V.: New Space Domain Processing Technique for Pulsed Laser Anemometry. Appl. Opt., vol. 29, Aug. 1990, pp. 3399–3417.

Williams, F.A.: Studies of Experiments on Droplet Burning at Reduced Gravity. Proceedings of the 4th European Symposium on Materials Sciences Under Microgravity, ESA SP–191, 1983, pp. 191–196.

Williams, F.A.: Ignition and Burning of Single Liquid Droplets. Acta Astronaut., vol. 12, no. 78, 1985, pp. 547–553.

Williams, F.A.: Droplet Burning. Chapt. II of Combustion Experiments in a Zero-Gravity Laboratory, T.H. Cochran, ed. (Vol. 73 of Progress in Astronautics and Aeronautics), AIAA, New York, pp. 31–60, 1981.

Williams, F.A.: The Role of Microgravity Research in Contributing to the Theoretical Foundations of Combustion. Proceedings VIIth European Symposium on Materials and Fluid Sciences in Microgravity, ESA SP–295, 1990, pp. 453–457.

Yang, J.C.; and Avedisian, C.T.: The Combustion of Unsupported Heptane/Hexadecane Mixture Droplets at Low Gravity. 23rd Symposium (International) on Combustion, Combustion Institute, Pittsburgh, PA, 1989, pp. 1619–1625.

Youngblood, W.W.; and Vedha-Nayagam, M.: Advanced Spacecraft Fire Safety: Proposed Projects and Program Plan. NASA CR–185147, 1989.

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This document updates an earlier overview that introduced the promise of microgravity combustion research and provided a brief survey of results and then current research participants, the available set of reduced-gravity facilities, and plans for experimental capabilities in the space station era. Since that time, several research studies have been completed in drop towers and aircraft, and the first space-based combustion experiments since Skylab have been conducted on the Shuttle. The microgravity environment enables a new range of experiments to be performed since buoyancy-induced flows are nearly eliminated, normally obscured forces and flows may be isolated, gravitational settling or sedimentation is nearly eliminated, and larger time or length scales in experiments are feasible. In addition to new examinations of classical problems, (e.g., droplet burning), current areas of interest include soot formation and weak turbulence, as influenced by gravity.

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